Water erosion on the northern slope of Al-Jabal Al-Akhdar of Libya.

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WATER EROSION ON THE NORTHERN SLOPE OF

AL-JABAL AL-AKHDAR OF LIBYA

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DECLARATION

I declare that no material in this thesis has previously been submitted for a degree at this or any other university.

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ABSTRACT

The northern slope of Al-Jabal Al-Akhdar, due to the relatively high amount of rain it receives and the good soils it has in some locations, is considered a reliable area for rain-fed farming. However, in this area, man has greatly altered the vulnerable environment and increased erosion rates. Water erosion is becoming a serious problem as a result of removing the natural vegetation cover to expand the agricultural area in order to fulfil the increasing demand of local markets for agricultural products.

This study therefore examines the importance of the different erosion factors of climate, topography, soil, vegetation cover and land use in accelerating soil erosion in the study area in order to find suitable solutions to this problem. The different factors, listed above, were first studied in relation to the presence and intensity of the soil erosion features, and then their relations to the rates of soil loss were analysed. Based on these relations, proper conservation measures were suggested. Data used have been obtained from fieldwork survey and existing reports, maps and statistics on soil, vegetation, agriculture and rainfall.

The results indicate that the soils of this area are generally shallow, contain a high percent of clay and low amounts of organic matter. Consequently, these soils have a low infiltration

rate and poor storage capacity. The variability of rainfall and its occurrence as relatively heavy showers characterized by high intensity, coupled with the poor soil properties, can produce runoff. The removal of natural vegetation and its replacement with a plant cover providing less protection for the land surface greatly increases the rate of runoff leading to accelerated soil erosion. The incidence and rates of soil erosion in the study area are largely controlled by the different types of land use and soil cover; however, they are modified by topography and amount of rainfall.

The results also indicate that runoff is the main agent of soil erosion. On the other hand, this surface water is very important for agriculture in the study area. Therefore, the suggested conservation methods aim both to minimise the effect of runoff and to achieve the maximum benefit from this water. By adopting farming methods that can maintain a protective cover of vegetation, soil organic matter will be increased, and hence its infiltration rate and storage capacity will be improved. Also the suggested structural methods, which are simple, cheap, easy to construct and maintain, can reduce runoff velocity, and thus increase infiltration rate by giving the soil more time to absorb water.

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Chapter 1

General introduction

Accelerated soil erosion by water is a world-wide problem. It occurs in many environments, but is most pronounced and poses the most serious problems in tropical and semi-arid areas (Morgan, 1986). Here a combination of climatic conditions, continuous vegetation clearance, farming practice and social and economic conditions ensures that soil erosion by water remains a serious hazard. In the Mediterranean basin, most of the coastal foothills and lower mountains have major erosion problems, not only because of their topographical features, but also because of their winter rainfall regimes (Chisci, 1981; Naveh, 1986). The dry warm to hot summer months make the vegetation susceptible to fire and overgrazing, because of the high temperature and the low herbaceous pasture production respectively. Furthermore, erosion risk is very high at the beginning of the rainy season, especially in cultivated areas, because of the absence of vegetation cover and the violent nature of the rainstorms of this period. Thus in some Mediterranean areas, such as the northern slope of Al-Jabal Al-Akhdar, Libya, where the dry summers are longer and the early winter storms are often violent, the level of soil erosion can be very high. This damage is further increased by the clearance of protective vegetation cover to enable the expansion of the cultivated area. As a result accelerated soil erosion is becoming a serious and increasing problem. Therefore, finding solutions to the threat of continued agricultural production posed by the soil erosion problem is an important priority for a country that has very limited agricultural lands.

Until the discovery of oil, the Libyan economy was mainly based on agricultural and pastoral activities. The discovery and exploitation of oil since the early 1960s changed the nation's economy and increased personal incomes. The result has been an increased demand for cereal grains, fruit, vegetables and livestock products. To meet these requirements, new areas have been cleared of natural vegetation either through government projects aiming to modernize traditional agriculture or through the action of individual farmers wishing to create new farms. This had its own implications in terms of land and water resources. Irrigation was extended and livestock breeding was expanded some times beyond the natural resources' capability (FAO 1969). Usually the accessible, deep soil areas were those selected for clearance, mostly located on lower slopes and valley floors. Continued increase in demand for agricultural products has resulted in the exploitation of new agricultural land not previously used. This new agricultural land comprises the steeper valley slopes. The exploitation of these steeper slopes with their shallower soils involved the clearance of the vegetation, usually by mechanical means, and the cultivation of the soils, mainly for cereal crops. The removal of vegetation and the cultivation methods employed have inevitably led to an increase in the amount and incidence of accelerated water erosion. The consequences of this accelerated erosion are far-reaching: the already thin soils on upper slopes are becoming shallower and the increased runoff is causing problems on the lower slopes. Here aggressive runoff has cut gullies 2.5 m or more deep. This loss represents a reduction in agricultural productivity, in addition to further costs arising from the sedimentation behind dams and in lakes and the deterioration of water quality. The enormity of this problem is apparent when realizing that most of these erosion features, gullies in particular, have developed in the last 20-25 years. Although the soil erosion problem is getting very serious, local literature dealing with erosion is not abundant, reflecting the relatively little attention that the subject has received in Libya.

Within Libya, the Jabal in general, and the northern slope in particular, are different from the surrounding areas to the east and south in many aspects. Being higher ground and jutting out into the Mediterranean sea they are cooler, wetter have a relatively rich vegetation cover and better soils than the surrounding regions. If the areas of reliable rainfed farming, in Libya, are defined as those receiving 300 mm or more of annual rain, then the total area is approximately 0.7 per cent of the total area of the country. However, only one-third of this small area is useable because of difficult terrain or poor soils (Allan, 1981). About half of this useable area is represented by the northern slope of Al-Jabal Al-Akhdar. Thus any reduction in cultivable area of the northern slope of the Jabal Al-Akhdar will have serious consequences for the agricultural potential of the whole country. This is exacerbated by the fact that of the cultivable area, the Jabal Al-Akhdar is probably the most favourable of anywhere in Libya.

At present the area under cultivation in the Jabal Al-Akhdar represents the land most suitable for agriculture. What now remains uncultivated includes areas of difficult terrain or shallow soils. Thus any increase of area will be into marginal lands, with steeper slopes and less fertile soils. Consequently, a move into these areas will increase both soil erosion and the incidence of flooding. In such a situation, it would appear wiser to concentrate on increasing yields from existing agricultural lands than to develop new lands. This can be achieved by applying conservation measures to protect these lands and by improving farming practice. As a result soil properties will be improved and its productivity will be increased.

Therefore the purpose of this study is to investigate the effect of soil erosion by water on the northern slope of Al-Jabal and to obtain the information required to design or develop appropriate measures to minimize the soil loss and other environmental impacts. In addition to increasing our understanding of the factors causing erosion and transport of sediment from the northern slope, this study will contribute to the improvement of agricultural techniques and the protection of the local environment. The study has four principal objectives:

1. To assess the present extent of erosion.
2. To analyse the relationships between the incidence and rates of erosion and soil erosion factors of rainfall, topography,

soil, land use and vegetation cover.

3. To estimate present erosion rates.
4. To make recommendations for a strategy for conservation.

In order to achieve the above objectives, the following investigations were performed:

a. Areas affected by features such as gullies or areas where topsoil is being removed were identified.
b. The relationship between the distribution and intensity of soil erosion features and land use and topography was assessed in each location.
c. The relative importance of various erosive factors - such as soil erodibility, vegetation cover, rainfall and topography - was studied to identify their influence on soil erosion in the studied sites.
d. Special attention was paid to the topsoil properties and their effects on hillslope runoff. These properties include soil texture, depth, organic matter content and infiltration rate. Variations in soil properties were related to position of slope and type of land use to determine which factor is controlling these variations, and also the erosional and depositional processes along the slope.
e. Soil erosion was measured on slopes of different angles, different land uses and under natural rainfall, to identify how these factors can affect the amount of soil loss.
f. Based on the results of the assessment of the present extent and rate of erosion, some measures to prevent or reduce erosion are recommended.

In the remainder of the thesis Chapter 2 presents a general review of the process of soil erosion by water and the factors affecting its intensity. In addition, special attention is given to what has been written about the Mediterranean region, Libya and the study area. Chapter 3 introduces the study area and outlines the main geographical characteristics, including elements of the physical environment, with a brief review of land use development since the Greeks. The methodology used in this study is presented in Chapter 4. Chapter 5 emphasises the main characteristics of the rainfall and how this factor contributes to the incidence of erosion. Chapter 6 presents a descriptive analysis of all site data to determine the importance of the different factors on the incidence of erosion, while Chapter 7 discusses their importance in terms of erosion rates. The statistical analysis of the influence that each factor exerts on the incidence of erosion is analysed in Chapter 8. Finally, Chapter 9 is devoted to outlining the main findings of the study, to suggest some measures that can help to minimize the present problem and to define further investigations in the different aspects of soil erosion in the study area.

Chapter 2

The problem of soil erosion by water: a literature review

2.1 General introduction

Soil erosion is usually divided into two categories: geological or natural erosion and accelerated erosion. Geological or natural erosion is the rate at which the land would normally erode without human disturbance. Geological erosion is an essential part of the processes operating on the natural landscape. Under conditions of natural erosion, soil formation and erosion are considered to be in a state of balance so that the depth of the soil remains roughly constant through time. On the other hand, accelerated erosion is the increased rate of erosion that often arises when natural conditions are modified by various land-use practices. Natural vegetation cover is an important factor in maintaining the state of balance and its disturbance tends to produce accelerated erosion (Finlayson and Statham, 1980). The rate of natural erosion varies enormously with controlling conditions such as climate, vegetation, soils, bedrock and landform. Worldwide, this rate is estimated to total some 9.9 billion tons of soil a year (Lal and Pierce, 1991). Added to this is an estimated total of human-induced, accelerated erosion of about 26 billion tons per year (Lal and Pierce, 1991). The patterns of accelerated erosion, reflecting a combination of natural and land use factors, are different from the patterns of erosion under natural conditions.

The accelerated erosion of soil by wind and water has been a major environmental problem since the first cultivation of land. It causes decline of agricultural productivity and deterioration of rangelands (Lindstrom et al., 1992). The natural loss of soil is often accelerated not only by agriculture and grazing but also by fire, urban development, and construction. Today, soil erosion by water is a serious and growing problem in many parts of the world, particularly in tropical and semi-arid areas, and it is increasingly recognized as a hazard in temperate countries including Great Britain, Belgium and Germany (Cooke and Doornkamp, 1990; Holy, 1980 and Morgan, 1986). Soil erosion by water is especially serious because it reduces soil productivity through the loss of topsoil, and it also degrades water quality when sediments and associated nutrients are transported by water to water courses (Mannering, 1982). Despite the extensive literature and the fact that the basic principles underlying effective conservation measures are well known, soil erosion remains a serious problem in many countries. This what made Blaikie (1985) suggest that soil erosion as a hazard is not simply a scientific problem; it is also very much connected with social and economic conditions. Convincing the farmer of the importance of erosion prevention measures is extremely difficult as the farmer's decision is influenced by different factors such as land tenure, crop marketing and short term profit (Blair-Rains, 1981). Therefore, the incidence of erosion depends on both biophysical processes and socioeconomic factors which determine the response of cultural practices (Higgitt, 1991). These practices, including proper conservation measures, are in turn dependent on an understanding of the complex interrelationship of the nature of the land and land use, farming practice, and the prevailing social, economic and political conditions (Bennema and

DeMeester, 1981).

2.2 Causes and consequences

According to the FAO (1981, cited by Sanders 1984), large areas of land at present under cultivation are suffering from various forms of land degradation, particularly soil erosion. It has been estimated that between 5 and 7 million hectares of land are at present being lost annually through degradation. If this is so, it is reasonable to assume that a much larger area is declining each year in its productive potential. Therefore, some areas which were previously suitable for cultivation are now only suitable for grazing, and areas that were suitable for grazing may only be suitable for low productive forestry (Sanders, 1984).

According to Christensen (1986), two main effects of soil erosion in agricultural land are as follows: on-site effects, which occur at farm level and are primarily reflected in damage to soil and crops, and therefore soil productivity changes associated with erosion; and off-site impacts, which occur when soil and chemicals are carried from farms in runoff or wind, causing water and air pollution and the problems of downstream deposition of sediments as well as ground water contamination and damage to man-made and natural structures. The degree of damage is determined, to a great extent, by the nature of the soil and its position in the landscape (Larson et al., 1983). Water bodies receive pollution loads from urban sources, such as municipalities and industrial plants, and rural sources, such as cultivated fields, forests and pastures. While in some areas erosion can cause both on-site and off-site effects, in others it might contribute to only one of these problems. For example, in the United States of America the annual discharge of pollutants, fertilizers and pesticides to waterways from agricultural land is about 1,100 million tons of suspended solids (Lal and Pierce, 1991). However, both on-site and off-site costs of erosion are substantial and the differences between them are crucial to the design of adequate conservation practices (Committee on Conservation Needs and Opportunities, 1986).

Studies like those of Larson et al. (1983) and Williams et al. (1981) have focused on the effects of erosion on soil productivity. Soil productivity is the capacity of a soil, in its normal environment, to produce a particular plant or sequence of plants under specified management systems (The National Soil Erosion-Soil Productivity Research Planning Committee, 1981). Soil productivity is lowered through loss of storage capacity for plant-available water, loss of plant nutrients, degradation of soil structure and decreased uniformity of soil conditions within a field (Williams et al., 1990). In addition, the reduction of productivity by erosion is a slow process that may not be recognised until the land is no longer economically suitable for growing crops (The National Soil Erosion-Soil Productivity Research Planning Committee, 1981). However, the loss of productivity begins when erosion affects the depth and nature of the rooting zone available to plants. The impact is especially serious when erosion reduces the depth of already shallow topsoil underlain by a clay layer, bedrock or other material unfavourable to plant growth. In a study conducted by Gollany et al. (1992) it was found that topsoil loss not only lowered yield, but also reduced the ability of the crop to respond to favourable conditions such as increased precipitation during the growing season. Walker et al. (1986) divided yield decline from soil erosion into two categories: repairable damage and residual damage. The first is usually associated with loss of soil fertility from erosion and can be restored by increasing organic matter, fertilizer, or other inputs. After treatment by the most economically effective inputs, there will, however, usually be residual yield damage due to deterioration in the soil environment. This is a result of reduced infiltration, diminished rooting zone, and impaired soil structure causing residual damage to yields that cannot be remedied economically.

Water erosion has effects on production costs, both short-term and long-term. Soil erosion and associated increases in water runoff frequently displace fertilizer nutrients and pesticides from the area of original application. Erosion can also directly damage crops, especially newly planted crops, when seedlings are washed away or inundated with sediment. Also in areas where severe gully problems develop rapidly, farm production costs can be increased through damage to farm equipment and the greater fuel and labour requirements needed to farm around gullies. Except in areas of concentrated flows, short-term effects of erosion on farm production costs can be gradual and subtle. In addition, it has proved difficult to diagnose these effects accurately or to distinguish them from other positive and negative influences such as varying weather, changing technology and improved crop varieties. Long-term increases in the cost of farm production occur when erosion severely, and sometimes permanently, alters the productive capacity of a soil to support crop production (Committee on Conservation Needs and Opportunities, 1986).

Some studies concentrate on off-site damages associated with soil erosion. Off-site damage is now an issue that some experts suggest may well represent the most serious social consequence of soil erosion on much of the cropland cultivated in the U.S. (Crosson, 1984). The most serious damage from erosion occurs, in some areas, after material and flowing water have left the field. These damaging effects include loss of lake and dam capacity, recreational value, flooding, blockage of navigable waterways, and damage to commercial fisheries, water conveyance systems, water treatment facilities, and municipal and industrial facilities (Committee on Conservation Needs and Opportunities, 1986).

2.3 Processes of soil erosion by water

In order to prevent soil erosion, which means reducing the rate of soil loss to the rate that would occur under natural conditions, appropriate strategies for soil conservation must be selected. This selection requires a thorough understanding of the processes of erosion and the factors affecting its intensity (Morgan, 1986; Toy, 1977). This understanding is also desirable in order to quantify adequately and predict the effects of different patterns of erosion on soil productivity and environmental quality. The factors which influence the rate of water erosion include rainfall, runoff, soil, slope, plant cover and the presence or absence of conservation measures. These factors can be grouped under three headings: energy, resistance and protection. The first group includes the potential ability of rainfall and runoff to cause erosion. This ability is termed erosivity which is the potential capacity of rain to cause erosion in given circumstances. The most important feature of the resistance group is soil erodibility, or the vulnerability of soil to erosion in given circumstances, which depends upon the mechanical and chemical properties of soil (Hudson, 1977). The protection group is concerned with factors relating to the plant cover (Morgan 1986).

The rate of soil loss is normally expressed in units of mass or volume per unit area per unit of time. Under natural conditions, rates are in the order of 0.0045 kg m^{-2} a^{-1} for areas of moderate relief and 0.045 kg m^{-2} a^{-1} for steep relief (Young, 1972). In comparison, rates from agricultural land, in the range of 4.5 to 45.0 kg m^{-2} a^{-1}, are classed as accelerated erosion. Theoretically, whether a rate of soil erosion is severe is judged in relation to the rate of soil formation. If soil properties such as nutrient status, texture and thickness remain unchanged through time, the rate of erosion is balanced by the rate of soil formation (Morgan, 1986).

In classic work in the western USA, investigations of the relationship between soil loss and climate showed that erosion reached a maximum in areas with an effective mean annual precipitation of 300 mm (Langbein and Schumm, 1958). Effective precipitation is the annual precipitation required to generate the given annual runoff at a standardized annual mean temperature of 10°c (50°F). However, this rate of erosion decreases sharply where there is increased density of vegetation (Langbein and Schumm, 1958). Work in other parts of the world indicates that rates may also be very high under very wet tropical climates.

Data related to the material carried by rivers in suspension can be used to provide a reasonable assessment of the global patterns of water erosion. According to these patterns the global average of sediment transported to the oceans is 150 t km^{-2} a^{-1} (Walling and Webb, 1983). This assessment reveals the susceptibility to erosion of semi-arid and semi-humid areas, especially in China, India, western USA and the Mediterranean lands. The problem of soil erosion in these areas is compounded by the need for water conservation and the ecological sensitivity of the environment, so that removal of the vegetation cover, for cropping or grazing or by fire, results in a rapid decline in the organic content of the soil, followed by soil exhaustion and the risk of desertification (Morgan, 1986).

Soil erosion by water is a two-phase process that consists of the detachment of individual particles from the soil aggregates and their subsequent removal by water. The two essential agents for this work are raindrops and overland flow. Deposition, a third phase, occurs when there is no longer sufficient energy to transport the particles (Cooke and Doornkamp, 1990). Each of these two types of erosion has its own set of forces and resistances: some forces for instance tend to encourage particle detachment, and others tend to resist it. Soil erosion by water depends on the relationship between erosivity of raindrops and running water on the one hand, and the erodibility of soil material on the other (Cooke and Doornkamp, 1990). The detached material is usually the topsoil, where plant nutrients are most heavily concentrated. The resulting exposure of subsoil leads to a lower rate of infiltration, increased runoff and further soil loss (Greenland, 1977). The severity of erosion depends upon the quantity of material supplied by detachment and the capacity to transport more material than is supplied by detachment. While most research emphasises the soil erosion of agricultural land, it is important to remember that it may also be a problem, for example, on forest lands after a fire or extensive tree felling or where vegetation-covered land is laid bare. As much as 90 per cent of erosion on agricultural land may result from the process of detachment and movement of soil particles as a result of raindrop impact (Cooke and Doornkamp, 1990).

Since it is known that raindrop energy increases the amount of soil in runoff, erosion could, therefore, be reduced by preventing raindrop impact (Hudson, 1981).

2.3.1 Erosivity

The nature of particle detachment and movement reflects the relationship between the characteristics of the rainfall and the those of the soil and ground surface. As mentioned earlier, soil erosion is determined by erosivity, erodibility and management. The latter is a wide term covering all the factors directly under man's control, such as the choice of land use, choice of crop and method of crop production (Hudson, 1977). The major properties of rainfall relevant to its erosivity are drop mass, size distribution, raindrop terminal velocity and rainfall intensity. The initiation of erosion by rainfall is due to the detachment of a soil particle from the bulk soil. The detached particle is then transported away in runoff. The force causing detachment is that associated with the impact of the individual water drop; kinetic energy of rain is assumed to be the factor which initiates detachment and erosion (Lal, 1977). Once size, terminal velocity, and intensity of drops are known, the total energy of any individual storm can be seen as the sum of the energies of its component drops. Hence there is a correlation between total energy and amount of rain and, as has been observed, the intensity of any storm (Lal, 1977). Although erosivity plays an important role in soil erosion, the distribution of high-intensity storms in relation to the crop calendar may also indicate the potential for soil erosion.

Measures of rain erosivity may be derived from rainfall characteristics; they are sufficiently correlated with the surface erosion (splash sheet and rill erosion) resulting from rainfall to be used in the prediction of soil loss. The relationship between rainfall, soil detachment and transportation has been described in several studies. Smith and Wischmeier (1962, cited by Morgan 1986) adopted a compound measure known as the EI30 index, to explain soil loss in terms of rainfall. The EI30 index is the product of kinetic energy E (in foot tons per acre inch) and intensity I (inches per hour), where I30 is specifically for the wettest 30-minute period during a storm. Hudson (1965, cited by Morgan, 1986), working in Zimbabwe, obtained a better correlation between the KE>25 index and soil loss than between soil loss and EI30. According to Hudson, Wischmeier's R value appeared less valid in southern Africa where it was found that erosion occurred generally when rain intensity was more than 1 inch per hour (25 mm h^{-1}). A new index of erosivity was thus developed showing the kinetic energy of rainfall falling with intensities greater than 1 inch per hour (KE>1). Also, in Sri Lanka better results were obtained with KE>1 rather than EI30, where KE>1 was used in combination with soil erodibility indices to demonstrate the potential for erosion in different regions (Bergsma, 1981).

In a study conducted by Lal (1977), tropical rains were classified as more erosive than temperate rains because of the high intensity of tropical storms. Also, these storms are usually accompanied by more high-intensity winds which further increases the erosive effects of rainfall.

For intensive tropical rainfall, the AIm index is better than either the EI or KE>1 in predicting soil loss, where A is the amount of rain per shower, and Im is the maximum 7.5 minute rain intensity. Rainfall and soil loss data collected by Lal (1976) in Ibadan, Nigeria, indicate a good correlation between soil loss and the AIm index.

In studying the badlands of southern France, Bufalo and Nahon (1992) defined an erosivity index known as the EKE (Effective Kinetic Energy). This index took account of pluviometric factors (intensity and kinetic energy of rainfall), the soil material factor (infiltrability of the soil) and those factors linking rain-soil interactions such as overland flow. The study area was a mountainous Mediterranean region characterized by marly slopes of low infiltrability and devoid of vegetation.

2.3.2 Erodibility

The ability of a soil to resist the action of erosive forces depends on its physical and chemical properties and the influences of cover, management, and conservation practices. Wischmeier (1977) and Morgan (1986) defined erodibility as the resistance of the soil to both detachment and transportation. Although soil resistance to erosion depends in part on the topographic position, slope steepness and the amount of disturbance created by man, it is the soil properties which are the most important determinants. Erodibility varies with soil texture, aggregate stability, shear strength, infiltration capacity and organic and chemical content (Kirby and Mehuys, 1987). In general, coarse texture indicates high permeability allowing less chance for runoff to be generated. For these reasons, coarse sandy soils are least susceptible to erosion (Holy, 1980). In addition, larger particles of soil are resistant to transportation because of the greater force required to remove them and finer particles are resistant to detachment because of their cohesiveness. Thus soils having medium texture, such as loams and silt-loams, are generally more erodible than soils with either high clay or high sand contents (Morgan, 1986; Wischmeier and Mannering, 1969). Richter and Negendunk (1977) and Evans (1980) examined erodibility in terms of clay content, indicating that soils with a restricted proportion of clay fraction, between 9 and 30 percent, are most susceptible to erosion.

Soil structure is defined as the arrangement of soil particles and the pore space between them. It includes the size, shape and arrangement of the aggregates formed when primary particles are clustered together into larger, separable units. It forms as a result of the complex interaction of texture, contained organic matter and chemical composition. In addition soil structure is a function of aggregate size and distribution (Campbell, 1978). Soil structure is relevant to soil erosion because it largely determines the rate at which water can enter the soil, as well as the resistance of soil particles to detachment by rainfall impact and their subsequent removal in surface runoff (Greenland, 1977). Therefore, deterioration of soil structure usually implies a loss of porosity, or pore continuity, or both; a loss of cohesive strength, often expressed by the formation of a surface crust or a pan, or by a general compaction in the subsoil (Lal, 1979a). In general, soils containing a large proportion of water-stable aggregates are more resistant to erosion than dense or compact soil, which is characterised by dispersed particles. The stability of any given structural organization is particularly important in relation to erodibility. This primarily concerns the tendency of particles to detach from aggregates. Smaller particles are more readily transported by moving water than larger ones, and hence if aggregates are stable against disruptive forces, little erosion will arise (Greenland, 1977). The quantity of organic matter contained in a soil also has an effect on its structure. The organic content of the soil has a greater capacity for absorbing and storing water than the mineral content. It also has an important effect in forming water-stable aggregates that increase the porosity and permeability of the soil. According to Campbell (1978) an increase of organic matter in the soil usually leads to an increase in its aggregate stability; this is primarily due to the polysaccharide content of the organic matter. In addition, this increased stability influences the soil infiltration, moisture content, aeration, and temperature, through its effect on soil aggregation (Campbell, 1978). In general, soils containing a low proportion of organic matter are subject to comparatively rapid erosion (e.g. in UK <2.5%). However, soil erodibility can be affected directly by the soil's chemical composition particularly the colloidal content, through its effect on the physical properties and indirectly because of its influence on the growth of plants (Bennett, 1939). The shear strength of the soil lies in its cohesiveness and resistance to shearing forces. It has been recognised that the cohesiveness of fine particles makes soil resistant to detachment. Morgan (1986) suggested that the use of the clay content of the soil as an indicator of erodibility is theoretically accurate because the clay particles combine with organic matter to form soil aggregates or clods, and it is the stability of these which determines the resistance of the soil.

The amount of soil erosion which occurs under given conditions is, however, influenced not only by the soil itself, but also by the treatment or management it receives. The differences in erosion caused by different management of the same soil are very much greater than the differences in erosion from different soils given the same management. In fact erodibility is influenced more by management than by any other factor (Hudson, 1981).

Wischmeier and Smith (1978) have attempted to quantify soil erodibility, or the tendency for a soil to erode under rainfall, as part of an attempt to produce a predictive model for soil erosion by water (see section 2.5 below). Erodibility or K values were determined by measuring soil loss from standard plots. Later the relationship between selected soil properties and soil erodibility was tested using standard statistical techniques (Wischmeier & Mannering, 1969). This statistical treatment of data led to the publication of a nomograph to predict the K value for soil (Wischmeier et al., 1971). This nomograph is based on the percentage of silt and very fine sand, sand, organic matter, structure and permeability. Although numerous indices of soil erodibility have been devised, the usual reference is to the USLE nomograph (Morgan, 1986).

The resistance of the soil to dispersal and soil permeability are factors of critical importance to erosion processes (Staver et al., 1991). Under identical conditions of moderate to intense rainfall, for example, a susceptible soil can erode 10 times faster than a less susceptible soil (Wischmeier et al., 1971). Generally, silts and fine sands are the least resistant to detachment; therefore, soils with 40-60 per cent silt content are considered highly erodible (Richter and Negendunk, 1977). Also, silty soils are usually characterized by low aggregate stability (Boardman, 1990).

The development of stable and erosion-resistant soil aggregates is promoted by a high organic matter content and a moderate amount of clay. High clay content, however, can lower the infiltration capacity of soil and promote increased runoff (Staver et al., 1991). Luk (1979) studied the effect of soil properties on erosion by wash and splash. He found that, in general, clay colloids promote soil aggregation, and the presence of humus is essential for the formation and maintenance of soil aggregates. Also, it has been noted that the organic content of the soil is more significant than the clay content and the effect of the clay is dependent upon its ratio to the organic content. Ekwue (1990) investigated how the organic matter contributed by grass and peat affects splash detachment and examined the relationship between splash detachment and organic matter content. It was found that aggregate breakdown was reduced by increased organic content. The soils with grass contained colloidal organic matter and breakdown was decreased by increasing aggregate stability; however, soils with peat contained fibrous organic matter and reduced breakdown by acting as a mulch. Thus, lowering the organic matter content will produce smaller, less stable soil aggregates, so that both the rate of water acceptance and the resistance of soil particles to detachment will be lowered (Imeson and Emmer, 1992).

Although organic matter and humic-clay complexes play a critical role in determining the stability of soil structure, two additional influences need to be considered as they may be of considerable importance in the soils of the study area. These are iron content and calcium carbonate content.

The role of iron in influencing the structural development and stability of certain warm temperate, sub-tropical and tropical soils has been recognised by a number of authors (eg. Duchaufour, 1977 and Wild, 1988). Duchaufour suggests that in these environments iron oxides occur as crystalline skins around clay particles, thus helping aggregation. Giovannini, Sequi (1976) and McIntyre (1956) suggest that the iron oxides form an iron-organic matter complex which acts as a cementing agent bonding particles together to give a stable structure. Work by Deshpande _et al._ (1968) has shown that the removal of iron from the structures renders them less stable and prone to collapse. The effectiveness of iron oxides in influencing structural stability however, remains contentious. Deshpande _et al._ (1986), Duchaufour (1977) and Wild (1988) argue that organic matter content remains the most important factor in the maintenance of structural stability. Indeed Duchaufour states that 'Intensive cultivation of fersiallitic soils decreases the amount of humus present and renders the structure unstable', this despite the high iron oxide content.

It is generally accepted that the presence of calcium in the soil encourages clay flocculation and the formation of soil aggregates (Wild, 1988). Calcium carbonate can also act as a cement, physically binding particles and aggregates together. Nevertheless, Payne (1988) suggested that excess calcium carbonate may reduce the cohesion between particles in moist clods and reduces the size of the water stable crumbs in the soil. In a study of the effect of calcium carbonate on soil erodibility in northern Greece, Silleos (1981) found that calcareous clays are erodible, unlike non-calcareous clays. This study concluded that the easy disintegration of calcareous soil aggregates contributes, by the action of splash erosion, to the detachment of fine particles and the sealing of soil pores. Such a mechanism induces crust formation, decreases the infiltration capacity and increases surface runoff. The slower drying of calcareous soils can also affect soil erodibility, because in the case of a second rainfall the soil is already saturated. The effect of organic matter on soil structure is of particular importance in the case of highly calcareous or silty soils where bonding forces between mineral particles are low. In the highly calcareous soils of southern Spain the relation between the micro-aggregation of the soil and the organic matter content was clearly indicated under both forest and cultivation (Imeson and Emmer, 1992).

2.3.2.1 Compaction, crusts and seals

In addition to producing a disruptive force, raindrops also provide a consolidating force which compacts the soil (Morgan, 1986). As a result of compaction of the soil surface the rate at which water can enter the soil is reduced and the runoff response to a unit amount of rainfall is consequently increased (Roels, 1984). Raindrops falling on an unsaturated surface can break down soil aggregates into smaller units or even primary particles and cause the vertical and lateral translocation of these particles (Le Bissonnais, 1990; Luk et al., 1990). This material may then fill the pores and accumulate in a densely packed layer (structural seal), usually only a few millimetres thick and characterized by greater density, higher strength, and fine pores (McIntyre, 1958). Also, these particles could be carried by subsurface flow, as suspended sediment load, forming a depositional seal when they settle (Gimenez et al., 1992). It has been suggested by Young (1972) that this is associated with the dispersal of fine particles from soil aggregates or clods which are redeposited to infill the pores.

The importance of crust formation in the erosion system is that the surface of the soil becomes sealed, so decreasing the infiltration capacity and depressional storage, until eventually overland flow takes place (Farres, 1978; Le Bissonnais, 1990;

Stern et al., 1991). However McIntyre (1958) found that the surface seal was a two-layer structure including a washed-in zone of 1.5 mm thickness overlain by a clay seal of 0.1 mm thickness which was ten times as effective in reducing infiltration as the washed-in zone. Bryan (1977) suggested that this clay seal is of great potential importance in the erosion process.

Römkens et al. (1990) suggested that 'crusting' is a more appropriate term for dry conditions, while 'surface sealing' refers to wet surface conditions. However, development of both enhances surface runoff and erosion, and prevents emergence of seedlings (Luk et al., 1990; Valentin and Bresson, 1992). In the case of dry aggregates and high rainfall intensity, slaking occurs. In this process a rapid closing of surface by small particles is the result (Le Bissonnais, 1990). In general, surface crusting is a process associated with the soils of semi-arid and arid regions that have a low organic matter content, high silt content and low aggregate stability (Helalia et al., 1988; Luk et al., 1990).

According to Levy et al. (1986) and Freebairn et al. (1991) soil crust development during rainfall often limits the infiltration of water into the soil. Crusts, formed either by mechanical action due to impacting raindrops or by chemical action such as hydration and dispersion, are composed of either a washed-in layer of silt or clay or a denser layer of particles created by compaction or sorting . According to Sharma et al. (1981) and McIntyre (1958), surface seals can form when raindrops strike the soil surface and create a thin layer of low hydraulic conductivity, which reduces the infiltration rate. In addition, this sealing usually ponds water at the surface, thus encouraging overland flow. However, if the transporting capacity exceeds the amount to be transported, any hollows will concentrate the flow and form a gully (Thornes, 1985).

Several mechanisms for the formation of surface seals have been proposed. Arshed and Mermut (1981) described a disruptional seal that formed due to structural break-down under raindrop impact or rapid wetting. McIntyre (1958) described a depositional seal formed by soil particles after transportation. Also described was a skin seal formed by the deposition of fine particles from suspension. In addition Agassi et al. (1981) proposed that seal formation was due to two complementary mechanisms:

1. physical disintegration and slaking of soil aggregates caused by water drop impact and water accumulating on the soil surface.
2. chemical dispersion of soil clays which can move and clog the pores beneath the surface or the washed-in zone.

As a consequence of these studies, Poesen et al. (1990) proposed that a rock fragment cover on a soil's surface can protect it from the beating action of rain and decrease its erosion potential. Even in a soil very susceptible to surface sealing, this results in a decrease in the amount of surface sealing, as well as an increase in infiltration rate and a decrease in runoff volume.

2.3.3 Vegetation cover

It was recognized long ago that vegetation cover is the most important factor in soil erosion control. Plants influence erosion directly as for example tree fall causing mass movement of the soil. Also the influence could be indirect as tree fall exposes soil to further erosion. In addition to the vegetation's impact on climate and hydrology (Viles, 1990), it protects the soil by intercepting raindrops and absorbing their kinetic energies (Kandiah, 1979; Lal, 1988; Verstappen, 1983). It reduces surface water velocity, allowing more time for infiltration, and contributes to the retention of the rain, therefore decreasing peak runoff (Thornes, 1985; Verstappen, 1983). Also plant stems and roots physically bind soil, improve infiltration rate by extracting moisture through transpiration and increase biological activity, leading to better soil structure. Consequently it reduces overland flow (Lal, 1988; Verstappen, 1983). However, the efficiency of roots in preventing soil erosion depends on the crop root system type. The fibrous root systems of grass-type crops, like corn and sorghum, are superior to the tap-root crops, like soybeans and cotton, because they have more extensive finer root systems, which in turn have a great stabilization effect on the soil (Mannering and Fenster, 1977). On hillslopes, vegetation provides an element of roughness and controls the rate of interception of rain in erosional processes (Thornes, 1990). A uniform dense short cover of grass leads to the greatest reduction in soil erosion by water (Cooke and Doornkamp, 1990;

Foster et al., 1985; Kandiah, 1979). Most soils are eroded when their vegetation cover is less than 5-10% (Evans, 1990). In some places a vegetation cover of 25-30% is sufficient to protect the soil from erosion (Elwell and Stocking (1976). However, when the vegetation cover consists of bunch grasses and bushes the flow can be concentrated between the clumps (Thornes, 1985). From the observations of De Ploey et al. (1976) flow can concentrate between plant stems and cause erosion even under a dense cover of grass. Kirkby (1969b) suggested that the lack of vegetation cover in the semi-arid regions is the main cause of high erosion rates.

In agricultural lands, it has been found that perennial crops result in low soil losses compared with seasonal crops such as wheat. Seasonal crops provide minimal ground cover prior to and just after germination and for several weeks afterwards; thus if this period coincides with heavy rains (particularly so for tropical rain-fed agriculture), then severe erosion can occur, (Lewis, 1988). Therefore, the management of growing crops and animals, the biological approach to soil conservation, is an effective strategy for soil conservation planning (Lal, 1988).

The beneficial effects of vegetation cover are not confined to living plants; mulches of crop residues provide protection from raindrops and improve soil aggregation when they decompose (Cooke & Doornkamp, 1990; Nill & Nill, 1993). However, Mannering and Fenster (1977) argued that the efficiency of residue depends on its quantity, distribution and durability. A high amount of residue, uniformly distributed, is the most effective for erosion control. In addition, residue durability depends on its type: residues with low carbon-nitrogen (C:N) ratios break down much more rapidly than those with high C:N ratios, such as corn or wheat. It has been found that surface mulches of crop residues are very effective in reducing soil detachment transport by reducing rainfall impact energy and runoff velocity, especially where slopes are gentle and soil permeability is moderate (Meyer et al., 1970). Ngatunga et al. (1984) suggested that if steep lands have to be used for cultivation the mulching and frequent use of grass in crop rotation should be advocated to conserve soil and water. According to Lewis (1988), mulching as a conservation practice is more effective than engineering methods even on slopes exceeding 30 degrees. Wischmeier (1977; cited by Mannering and Fenster, 1977) reported that the regular incorporation of crop residues by ploughing gradually increases the amount of organic matter in the soil and improves water intake and soil structure. Roose (1980) noticed that in some parts of tropical Africa, after clearing the forest, a rapid decrease of aggregate stability and infiltration rate occurred. The aggregate stability usually stabilises at a lower level under crops, but the rate of infiltration decrease is a function of soil type, crops and cultivation techniques. Lal (1979b) suggested that the rapid decline of infiltration rate in tropical soils is a result of natural vegetation removal and the introduction of mechanized tillage operations resulting in the disturbance and exposure of soil.

The relations between vegetation cover and soil erosion are complicated. In addition to the fact that the protective effect of vegetation varies with the time of year, some plants may increase raindrop impact and concentrate runoff (Cooke and Doornkamp, 1990). On the leaves of high vegetation, droplets often larger than the original may reform (Lal, 1988). Morgan et al. (1986) found that the energy of leaf drip increases with plant height. Therefore, material in contact with the soil surface, such as low-growing plant cover, is usually very effective, because it can prevent detachment by intercepting drops and there is no fall distance for drops to regain energy. A further reduction in raindrop impact is provided when such material reduces runoff velocity which increases the flow depth; the latter in turn cushions raindrop impact (Foster and Meyer, 1977). Furthermore, tall-growing vegetation may reduce ground cover by shading (Lal, 1988). Concentration of runoff can be caused by growing crops in rows, especially if these run up and down slope. Widely spaced rows (e.g. maize) can cause severe problems.

2.3.4 Landform

This includes the length, steepness and shape of slope. Slope is a very important factor in water erosion because of its effect on both the volume and the velocity of any water which runs off (Bryan and Poesen, 1989). In addition, the morphological characteristics of the slopes are of major importance in affecting processes of water erosion (Verstappen, 1983).

Slope analysis is of great value in assessing the natural resources of an area, and consequently in geographical studies of an applied nature (Young, 1964). Morphological mapping based on slope angles has been shown to be important in the compilation of landform maps for land planning purposes. Such morphological units, based on slope angles, are observed to be associated with technical-economic practices, soil erodibility, farm size and land use patterns, which are some of the factors taken into consideration in land utilization plans. Therefore, slope angle is an important element in determining how the land is used, and a classification of slope angles is important for land planning purposes (Olofin, 1974).

In general, the greater the increase in degree and length of slope the greater the amount of erosion. On steep slopes the velocity of overland flow tends to be relatively high and the infiltration rate lower than on gentler slopes of the same material. If water runs quickly, its chance of being absorbed by the soil is reduced. The increasing velocity of water increases its ability to dislodge and carry away soil (Sanders, 1984). Slope length affects the volume of water which accumulates on it. The build-up of large quantities of surface runoff, with its greater velocity and depth on longer slopes, increases the likelihood of erosion. On flat or gently sloping land, a film of water forms on the surface during intense storms. This helps to dissipate raindrop energy (Sanders, 1984). However, the relationship between slope length and erosion is complicated by the shape of slope (Hudson, 1977).

Slope shape, described as concavity or convexity, has an important effect on soil erosion and on the subsequent treatment of a particular piece of land to control erosion. In the case of a concave slope, erosion increases on its upper section when runoff moves quickly. This runoff slows down and deposits some or all of its load when it reaches the lower slope. A convex slope, on the other hand, is susceptible to erosion more on its lower section, and the load is deposited either on lower flat lands or directly into streams. The distribution of erosion is more complex in the case of straight slopes (Verstappen, 1983). When the slope is regular or rough the movement of the water is impeded. Some of it is temporarily held back; thus the infiltration rate increases and runoff is slowed down.

The overland flow ultimately produced may be of various types and intensities, resulting in specific erosion processes (sheet, rill and gully). The vegetation cover of the slopes concerned may completely alter the situation of overland flow and erosion by water. Therefore, the importance of hillslope flow processes in a particular region, and more precisely on each individual hillslope, is affected by climate, geology, physiography, soil characteristics, vegetation, and land use. Consequently, differences should be expected between the results in regions of different geography (Dunne, 1978).

2.4 Modelling of erosion

Rates of soil erosion vary over the landscape and even over a small field. Also climate variability and changes in land use make these rates vary over time. Therefore direct measurement of soil erosion is always problematic. Consequently, estimation methods are often used to assess the magnitude of erosion, to identify areas of excessive erosion and to project long-term changes in crop production from soil erosion (Foster, 1988). These methods are useful and efficient tools in solving problems of conservation practice, and increasing understanding of the process of erosion (Hudson, 1981). Prediction methods of soil erosion were described by Foster (1988) as packages of scientific knowledge that effectively transfer technology from the researcher to the user. Therefore, the models are means for better understanding erosion and erosion control systems (Wischmeier, 1984). They are considered to be convenient tools for extrapolating information where specific field situations have not been studied.

A model is a method of predicting soil loss under a wide range of conditions (Morgan, 1986). Three types of model can be identified: black box, grey box and white box.

1. Black box, which is the simplest and based on studying the main inputs and outputs. It relates sediment loss to either rainfall or runoff. However, a main disadvantage of this type is that it does not indicate why erosion occurs. Therefore, it cannot indicate control measures or help to assess their effectiveness. An example of this type was developed by Langbein and Schumm (1958), as referred to earlier.

2. Grey box, where some details of how the system operates are known. This type of model is based on defining the most important factors and relating them to soil loss through the use of observation, measurement, experimental and statistical techniques. The relationship between sediment loss and a large number of variables is often expressed in a regression equation.

The Universal Soil Loss Equation (USLE) is an example of empirically-based technology. It was designed to predict long-term average soil losses through sheet and rill erosion from USA agricultural land under specified cropping and management systems. Also the equation was developed primarily to provide a planning tool for conservationists to guide their choice of conservation practices particularly suited to a specific field. The USLE has been used for more than two decades in conservation planning (Elliot et al., 1991).

The formula of the equation is:

$$A = R \quad K \quad L \quad S \quad C \quad P$$

In this equation, A is soil loss in tons acre^{-1} year^{-1}. R is an average annual rainfall erosivity factor. This factor was designed to quantify the effect of the raindrop impact and to provide relative information on the amount and rate of runoff likely to be associated with the rain (Risse et al., 1993). The R value for a given period can be obtained by using EI30 index, which is the product of a rainstorm's kinetic energy and its maximum 30 min intensity. Individual storms can be added to give weekly, monthly or annual erosivity values (Nortcliff, 1986). K, the soil erodibility factor, is the rate of soil loss for a plot of 72.6 ft long and 9 percent angle, in a continuous fallow, tilled up and downslope. L and S are length and slope steepness. L is the ratio of soil loss from the field slope length to that from the standard plot length, while S is the ratio of soil loss from the field slope gradient to that from a 9 percent slope (Wischmeier and Smith, 1978). C is a cover factor and P is an erosion control practice factor. C is the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled, continuous fallow conditions. P is the effect of farming practice such as contour farming, terraces and strip cropping. Therefore, P is the ratio of soil loss with a specific support practice to the corresponding loss with up and downslope cultivation. The USLE as an empirical method does not explicitly represent erosion processes (Foster, 1990). Also it generally excludes gully or streambank erosion, snowmelt erosion and wind erosion (Meyer, 1984). In addition it does not take into account existing soil moisture in estimating soil loss (Hart, 1984). Consequently USLE has some limitations. However, these limitations do not constrain its validity, but do limit its predictive effectiveness.

A revision and updating of the USLE by Renard et al. (1991) was based on reviewing its data base, analysis of data not previously included in this equation and theory describing fundamental hydrologic and erosion processes. The result of this updating is known as RUSLE or the revised USLE. In RUSLE, some improvements were made to allow the original limitations to be overcome. The parameters of the original equation are still the same, but its factors were developed through improving the values of each factor or by including new subfactors. For instance the values of R factor were reduced on flat slopes because pounded water reduces the erosivity of raindrop impact. In addition to developing a K factor for soils that were not included in the USLE erodibility nomograph, this factor was improved by taking into consideration the seasonal variability of its values. The L factor was improved by using different slope length relationships, such as slope length as a function of steepness or soil susceptibility to rill erosion. C factor should be calculated as a function of prior land use, canopy, ground cover and surface roughness.

3. White box: increasing knowledge of erosion mechanics and erosion processes interrelationships has increased the scope for developing physically-based models. Along with this goes a switch from using statistical techniques to employing mathematical ones. An advantage of such models is that they incorporate greater understanding of the causes and processes of erosion, including generation of flow, sediment detachment, sediment transport and deposition (Foster, 1990; Scoging, 1980). The main constraints for an erosion model are thought to relate to conservation of mass for sediment and water, and to meeting boundary conditions at plot boundaries, divide, and slope base as relevant (Kirkby, 1980).

For example, Moore and Burch (1986) developed a physically-based model to predict the effect of topography on erosion and deposition on two-and three-dimensional terrain. Their analysis, for both hypothetical and real landscapes, showed that hillslope shape, slope, slope length and catchment convergence and divergence play important roles. This model only accounts for the effect of topography and ignores the effects of cover and soil detachment. These two aspects of erosion were ignored for two reasons: first, to isolate the effects of topography, and second, these aspects of erosion processes have been examined in detail by other people and, could, if desired, also be incorporated into the proposed model.

In modelling soil erosion some basic principles must be taken into consideration. These principles are efficiency, range of validity and constraints (Kirkby, 1980). The efficiency comes from giving the greatest details to the processes which have the greatest influence on the overall behaviour of the model. Validity can be addressed by considering applicability, utility and accuracy (Foster, 1988). However, no practical model is valid for all conditions, but each is best at performing a particular task. However, a model can also gain efficiency by maximizing its range of validity for a given number of parameters.

2.5 Soil erosion in the Mediterranean Basin

Climatic characteristics of the Mediterranean region include rare freezing, hot summers with at least two to three dry months and cool rainy winters. Mean annual rainfall can vary from 20-25 mm in the Mediterranean deserts to 2000-2500 mm on mountain slopes or locally in maritime areas exposed to rain-bearing winds. The Mediterranean basin cannot be regarded as a region of homogeneous climate. A relatively wide range of marked climatic zones exists, varying from moist to dry (Imeson and Emmer, 1992). Subclimates ranging from hyper-arid to hyper-humid can be differentiated based on the length of both dry and rainy seasons, together with the total amount of rainfall. There are also specific types of vegetation corresponding to these classes of subclimate (Davidson, 1991; Le Houerou, 1992). Beside its richness and genetic diversity, Mediterranean vegetation is characterised by its vulnerability. Vulnerability is a result of the ecological conditions, particularly the climate, i.e. a mild winter and a long summer drought, and the result is high susceptibility to fire and overgrazing (Le Houerou, 1981). From the biological viewpoint winter stress is very important. It can be non-existent, light, and mild, or intense and prolonged, depending on latitude, elevation and continentality. Cold stress is a potent factor for determining vegetation distribution patterns, crop selection and land use (Le Houerou, 1992).

Precipitation often falls from storms of high intensity that produce torrential runoff (Bradbury, 1981). In some areas with semi-arid environments, such as south-eastern Spain, the long and excessively dry summer is occasionally punctuated by heavy and intense convective rainfalls in late August or early September which cause heavy flooding and high levels of damage (Romero-Diaz et al., 1988). Because of these violent storms, Le Houerou (1981) described the Mediterranean climate as one of the most aggressive in respect of erosion. Also, in regions such as the southern Mediterranean, cracks can form by desiccation during dry summers causing extreme dissection of the slopes and creating a badland topography (Paskoff, 1973). A major problem in the winter rainfall climate in this region is that the rainfall, which causes erosion, does not coincide with the vegetation cover that protects the soil surface, especially in cultivated cropland and heavily grazed pasture. During the period from October, when the first rains usually come, until December, when sufficient growth may develop to protect the soil, the soil is exposed and highly vulnerable to the ravages of water erosion (Finkel, 1986). As a result of the climatic conditions, areas with Mediterranean type climates are traditionally classified as areas with high erosion rates (Brown, 1990; Saunders and Young, 1983 and Vita-Finzi, 1969).

In general, the Mediterranean climate does not favour the development of a dense vegetation cover on most slopes, which are poorly stabilized at ground level. However, upper storey vegetation may approach 100% cover when not modified by man or fire. The degree of variation in ground cover determines the access that erosion agents have to the land surface. When vegetation cover is relatively impoverished, high runoff, resulting from concentrated precipitation and steep gradients, produces almost all of the erosion and deposition. It has been found that very high soil erosion rates by surface wash, especially on steep slopes, were a result of heavy rainfall and intense deforestation (Calvo and Cervigon, 1988). In general, high relief and barren slopes suggest that the rate of erosion is higher than that of soil development.

The Mediterranean Basin has suffered perhaps more than any area in the world from degradation of the landscape, due not to the climate, but to human misuse of the land (Davidson, 1991; Morgan and Rickson, 1990; Trabaud, 1981). In some areas erosion has been continuous and intensive since Neolithic times (Romero-Diaz et al., 1988). According to Sevink (1988), accelerated soil erosion is a serious problem in this region because of the changes in the slope runoff characteristics. These changes are the result of human disturbance of vegetation cover and topsoil, by intensive agriculture, deforestation and forest and shrub fires. According to Francis et al. (1990), deforestation in the semi-arid region of south-east Spain has increased the intensity of the erosion and the result is the familiar and active process of desertification. However, in this region, burning is an old and common practice used to clear forests, wood and shrublands, for pastoral use and cultivation (Naveh, 1975). As well as the fires caused by man, lightning and volcanic eruptions were the cause of many large-scale fires in geological times, especially since the Last Interglacial desiccation, when the main Mediterranean climate patterns and vegetation types became finally established (Butzer, 1972). Imeson and Emmer (1992) stated that forest fires have an influence on the water balance by decreasing the evapotranspiration. This in turn can affect the salt balance of the soil, by promoting ground water transportation on the slopes, which leads to salt seepage at the slopefoot positions and increased salinity in streams. Such salt seepage can enhance soil degradation (Sommerfieldt and Mackay, 1982). There is also the fact that fire can cause a loss of the ecto-organic horizons and a decrease in the organic matter content in the upper soil horizon, so that the availability of soil nitrogen may be reduced significantly and structures weakened. In addition, expansion or contraction of natural vegetation in the Mediterranean region across the centuries has corresponded closely with changes in the agricultural activity and density of the population. Trabaud (1981) and Le Houerou (1992) divided the Mediterranean basin into two parts, northern and southern, each with different land use patterns due to different human pressures. In the northern part the overall land was divided into 36% farmland, 29% forest and shrublands and 22% rangelands with the rest as non-agricultural land. From 1965 to 1985, the trend was towards increased uniformity of land use, with farmland and rangeland abandonment in the marginal areas, and compensated for by a sharp increase in forestation and urbanization. On the other hand, over the same period the opposite trend was witnessed in the southern and eastern basin. Forest and shrublands receded by 3% while cropland expanded by 5%. If this situation prevails, destruction of vegetation cover will result in heavy wind and water erosion. At present the average rate of water erosion is 5-10 t ha^{-1} a^{-1} and might increase by a factor of five. The situation in the northern basin will be exactly the opposite.

Also the expansion of the human population, in the southern part, is much faster than that of food production. Between 1965 and 1984 the average population growth was 3.2% per annum, while cereal production grew by only 0.2% per annum. Such a demographic explosion will result in the further clearing of natural vegetation to expand the agricultural area.

2.6 Previous studies of soil in Libya and Al-Jabal Al-Akhdar

In addition to some papers and reports, four main studies have been undertaken in Libya and in the study area. However, most of these studies deal either with the influence of soil on agricultural potential or the general characteristics of the soils as based on soil profile description. The problem of soil erosion by water was only mentioned briefly in some pilot studies and no clear attempt was made to determine the importance of the factors that influence soil erosion.

The first was a report by FAO (1969) made by a team of experts on the available information on water resources and giving advice on measures for the development of water resources and water conservation in northern Cyrenaica.

A pilot area, representative of the region's natural features, was selected for detailed investigation. This was aimed at obtaining a comprehensive analysis of the water situation and its influence on the agricultural potential of the studied area. Particular attention was given to the influence of climate on land use capability. The study concluded that:

1. Rainfall was the most important factor controlling land use capability; therefore, the study area was divided into five agricultural zones, three of which were situated in Al-Jabal Al-Akhdar.

2. The agricultural potential of the study area is limited by insufficient rainfall and the scarcity of deep arable soils capable of storing and efficiently utilizing what rainfall is available. Only about 7 percent of the total dry farming region (Al-Jabal Al-Akhdar) consists of arable land; the major portion is made up of lithosols and rock outcrops capable only of supporting brush and poor pasture vegetation.

The second study was conducted in 1975 by GEFLI (Groupement d'Etudes Francais En Libya). This was a study of the erosion protection of 100,000 hectares in Al-Jabal Al-Akhdar. The study was conducted at seven sites, areas representing an average area of 14,000 hectares. A field survey was carried out by two specialists, a pedologist and an erosion control expert, to determine the land use of each plot along with the corresponding erosion control facilities. At each site the environmental data of soil, slope and land cover were analyzed. In addition, the Universal Soil Loss Equation (USLE) was used to estimate the action of the different environmental factors as well as the effect of the remedies proposed. The results were compared with those obtained in Tunisia, where similar conditions exist.

The third study (Soil-Ecological Expedition Report, 1980) was carried out by a Russian team. This was a study of the soil and ecology of the northern part of Libya. This region was divided into three areas:

1. The western part (Tripolitania): a total area of 1.6 million ha with an average annual rainfall of more than 200 mm.
2. The eastern part (Benghazi region): a total area of 1.4 million ha with an average annual rainfall of more than 200 mm.
3. The Pasture Central Zone: a total area of 0.5 million ha with an annual precipitation from 50 to 150 mm.

As far as soil erosion is concerned, this study classified the northern slope of the Jabal as an area dominated by water erosion.

The fourth was a study of Kouf National Park carried out in 1981-1983 by ACSAD (the Arabic Centre for Arid land and Desert Studies). The main objectives of this project were to conserve and improve the natural resources and wildlife of the Kouf area. Al-Kouf is one of two main wadis draining the surface water of the northern slope of Al-Jabal Al-Akhdar.

One part of this study was a quantitative and qualitative evaluation of natural grazing resources through a detailed vegetation survey of 23 sites representing the major vegetation types of the Kouf watershed. These sites were divided into three levels of ecological developmental units. The study discussed the characteristics of each unit, the potential of productivity, and the approaches to improvement and management. Land use in the study area was mainly that of grazing, with sheep and goats as the dominant animals in the southern part and goats becoming dominant in the central part where the vegetation cover consisted of trees and shrubs. Cattle were found in the flat areas particularly on valley floors and the coastal plain.

The second part of this study was the construction of a soil map on a scale of 1:50,000. This and the soil study in the area were based on seventy soil profiles, 32 of which were analyzed. Soil types were classified according to the USDA classification system. The main soil types are: aridisols, entisols, inceptisols, mollisols and vertisols. Some of the main characteristics of these soils are:

1. Biological activities are very well expressed on the whole project area (earthworms, ants, spiders etc.)
2. Soil structure is predominantly prismatic.
3. The cation exchange capacity was generally high due either to high clay or to organic matter contents.
4. Deep cracks, generally less than 1 cm in width, are present in most deep soils.

However entisols are the predominant soils in the project area. The main characteristics of these soils are their shallow depth, which does not exceed 25 cm, their reddish colour and their clayey texture.

A study of the erodibility of some Libyan soils was conducted by El-Asswad and Abufaied (1994). They investigated the erodibility of three major soil types from the south-eastern areas of Libya. After determining the soil chemical and physical properties, these soils were subject to a simulated rain for two periods of 30 minutes each. The first period represented a heavy rain on dry soil, and the second represented a heavy rain on wet soil. Runoff volume and amount of soil eroded for the two events were measured. The main result was that the erodibility of these soils decreased with the increasing content of clay and silt and the decreasing content of very fine and fine sand. However, their main conclusion was that erosion can be a serious problem on the land of arid and semi-arid regions.

Atkinson (1969) explained the main characteristics and the important process that form Terra Rossa. These characteristics were compared in three soil profiles from similar fields in different areas. Two profiles were described by the author, one was taken from the Northern Highlands of Jordan, and the other from South-Central Anatolia, Turkey. The third was described by Buru (1968), and was taken from Al-Marj Basin, which is located in the Western part of the first bench of Al-Jabal Al-Akhdar. The first two profiles were generally similar while the third has different physical and chemical properties. The Libyan example was characterised by lighter texture, less clay and more sand than the other two examples. This low clay content was reflected in its lower values of total exchangeable cations, and was attributed to colluvial inwash of sand. The three profiles, however, showed deficiencies in major nutrients such as organic matter and low content of nitrogen and phosphates.

2.7 Conclusion

One of the objectives of this study is to suggest some appropriate measures to prevent erosion. Therefore, a basic understanding of the process of soil erosion by water and the factors affecting its intensity is a first and indispensable step towards sound soil conservation.

In general, the rate of soil erosion is determined by five factors: climate, topography, soil, vegetation cover and land use. Although each of these factors is dealt with as an independent variable, a complex interrelationship exists among them. For example, the amount of erosion is affected by the intensity and duration of rain, but a dense cover of vegetation can reduce the effect of rain. Also, soil through its properties, especially infiltration rate, can play a major role. Soils containing a high amount of clay usually have lower infiltration rate than soils of high amount of coarse sand; therefore, the chance for runoff occurrence, and hence erosion, is higher in the case of the former than the latter. Thus the potential erodibility of a site is represented by the combination of these factors. However, soil erosion is a process that occurs at varying rates over the landscape and even within a field; therefore, its direct measurement is impractical. Consequently, erosion prediction methods are used to assess the different impacts of soil erosion and to select conservation methods.

In the study area where the environment is vulnerable, all the factors listed above, especially land use, are influencing soil erosion by water. The soils are generally shallow, containing a high percent of clay and a low amount of organic matter. Consequently, these soils are of low infiltration rate and poor storage capacity. Therefore, runoff will be increased and hence erosion. The variability of rainfall and the occurrence of occasional relatively heavy showers characterized by high intensity can produce runoff. The removal of natural vegetation and its replacement with a plant cover providing less protection for the land surface is the main factor that accelerate soil erosion. The combination of these factors in addition to topography has increased the rate of soil erosion by water in this area.

Chapter 3

The study area

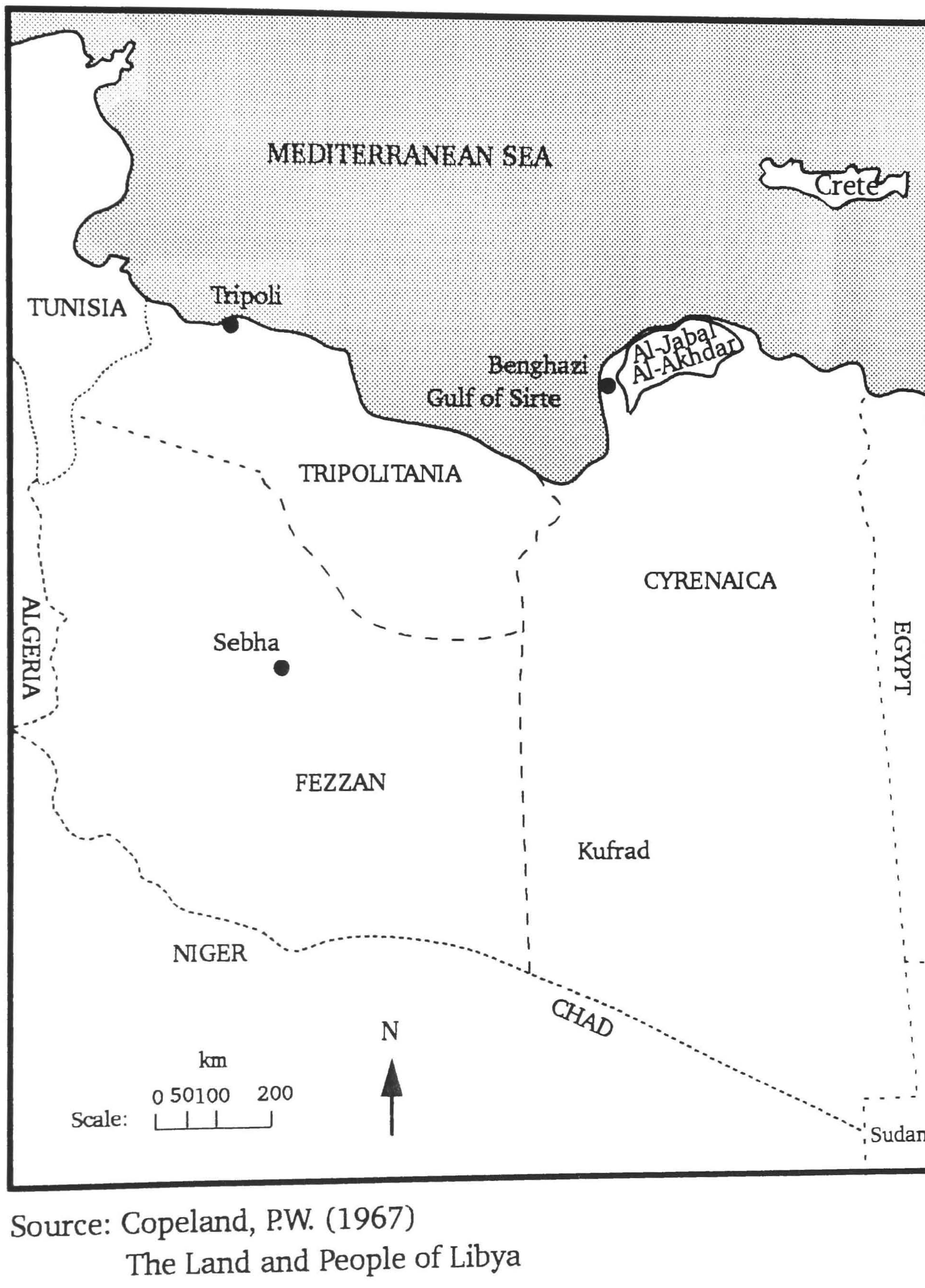
3.1 Location

Cyrenaica is the name of the eastern part of Libya. This part extends eastward from about 18° 30′ E (west of Aghaila) to the Egyptian border at about 25° E and southward from the Mediterranean coast south to the border of Chad and the Sudan (Figure 3.1). The total area is 780,000 sq. km approximately (Goudarzi, 1970). The Jabal Al-Akhdar, or Green Mountain, is a mountainous region located in the northern part of Cyrenaica. The latter is a region of simple relief with the Jabal as the only area of high ground. The Jabal is composed of terraces or benches in the north and a complex of fans, badlands, and desert plains in the south. In an FAO study (1969) the Jabal Al-Akhdar was delimited by the isohyet of 300 mm average annual rainfall. The 300 mm isohyet has also been chosen here as the boundary to separate the Jabal from the coastal plain in the west and the semi-desert in the south, a total area of about 6,750 sq. km.

3.2 Topography

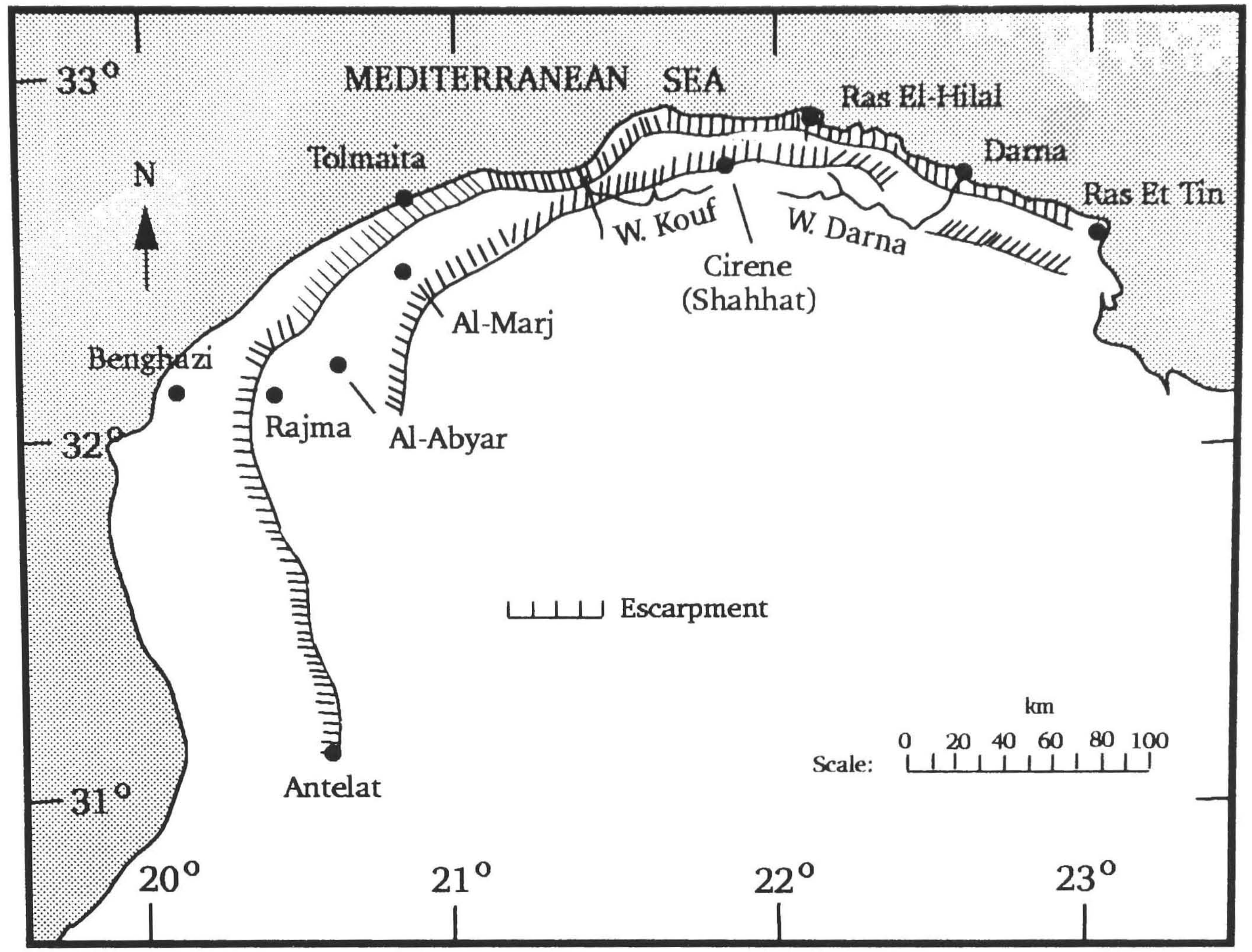
The Jabal is roughly elliptical and its length from east to west is about 250 km. All its highest points, some over 850 m above sea level, lie to the north, within 40 km of the coast. To the south and east the ground descends gradually; however, the Jabal is sharply defined on its northern and western sides, by steep slopes which take the form of successive escarpments (Figure 3.2). Although there are no signs of pronounced fluvial activity in the Jabal, a widespread aggradation has taken place in historical times (Vita-Finzi, 1969).

Figure 3.1 CYRENIACA AND AL-JABAL AL-AKHDAR



Source: Copeland, P.W. (1967)
The Land and People of Libya

Figure 3.2 TOPOGRAPHY OF THE STUDY AREA



Source: McBurney and Hey (1955), Prehistory and
Pleistocene Geology in Cyreniacan Libya

The basic configuration of Al-Jabal is a step-like arrangement of alternating benches and escarpments rising to 850 metres above sea level. There are two main escarpments, further apart in the west but drawing gradually closer together eastward, both roughly parallel to the coast. A large portion of the two benches, especially the second, is dissected by wadis, giving the Jabal a predominantly hilly to mountainous appearance. In addition, the low local relief has aided the development of substantial karstification in some portions of the benches.

The lower (first) escarpment starts at Antelat (31° 7′ N, 20° 35′ E) about 100 m above sea level, and rises gradually to about 300 m in the vicinity of Rajma. From Rajma it swings northwestward and approaches the sea near Tolmaita; continues eastward at about the same elevation, and then rises to a height of about 500 m at Ras el Hilal. It then slopes downward to a height of 250 m near Darna, beyond which it abruptly loses its prominence.

The second escarpment originates in a conspicuous feature near Al-Abyar at an elevation of about 450 m and rises gradually to about 625 m near Cirene (Shahhat), beyond which it descends gradually to the east (Plate 3.1). Inland for 10 to 20 km from this upper escarpment, the land rises somewhat irregularly to greater heights, reaching a maximum of 882 m some 20 km south of Cirene.

Plate 3.1 The second escarpment (back ground) from Lussaita site, located on the first bench.

The first bench is an undulating plateau of between 200 and 400 m altitude, with an average elevation of 320 m, approximately 10 to 15 km wide, and extends as an arc over 250 km to a point a few km east of Darna. It is separated from the coastal plain by the first escarpment which is sharply defined, usually very steep and cut by some very short wadis. The relief of the first bench is characterized by well-developed karst erosion in the form of sinkholes, dolines and depressions and the presence of small alluvial fans extending from the foot of the second scarp-face, also with some wadis cut deep into this bench (Kanter, 1967). Some of these wadis originate on the second escarpment, but most originate on the first bench, and all have a northerly direction. These features give this bench a high local relief.

The second bench is located to the south of the first bench and separated from it by the second escarpment. This bench has a more mountainous appearance than the first; the wadis are cut deeper into the rock, the slopes are steeper and the altitude is generally between 500 and 700 m, with the southern part of this bench rising to the highest point in the Jabal at 882 m. Also it has a mountainous aspect with deep wadis and steep slopes. The drainage divide, which is seldom more than 40 km inland, is the southern limit of this bench. In general, both benches rise slightly toward the south and are formed largely of Miocene limestone with some older Oligocene, Eocene and Cretaceous rocks.

From the watershed southwards, towards the desert, the region has an aspect of hilly relief and gentle slopes, and the wadis gradually descend into a series of playa lakes in the Balta zone, where most of the drainage of the southern slope is collected. Beyond the Balta zone, the land extends without marked slope or notable features until it merges with the desert.

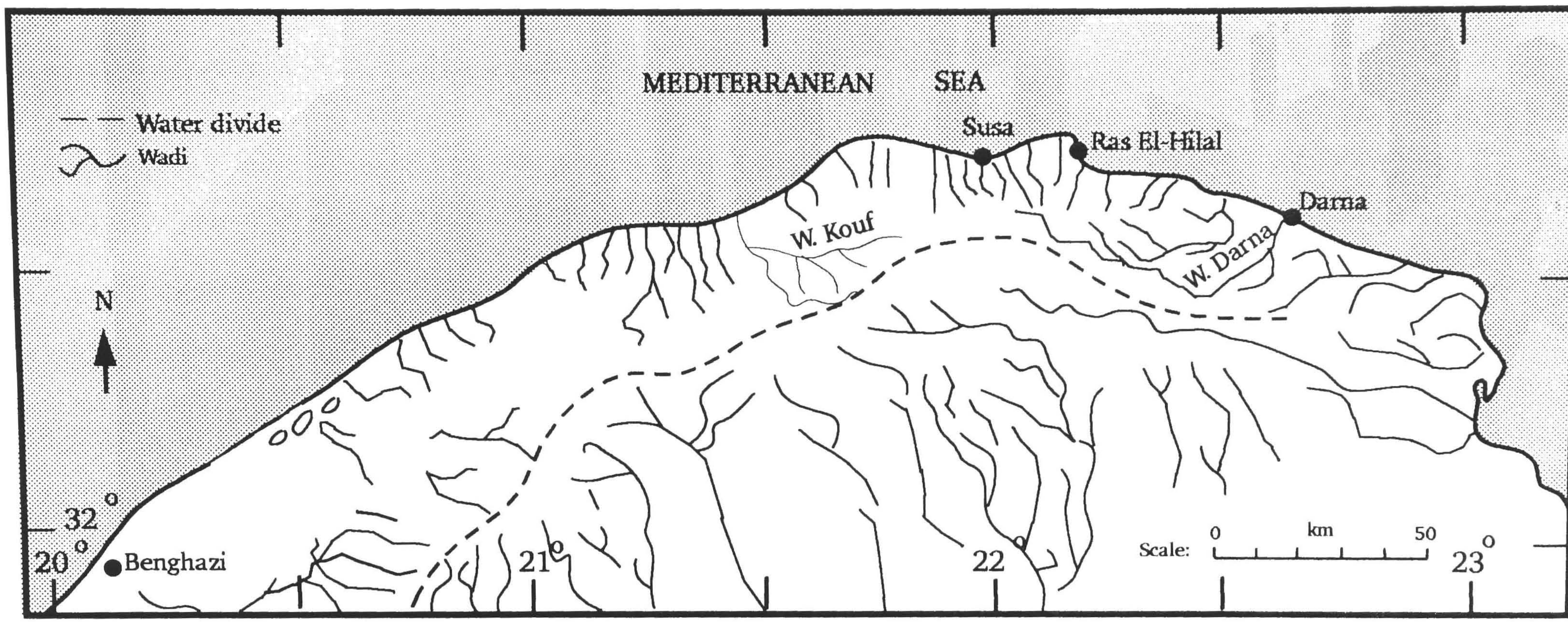
According to GEFLI (1975), if the escarpments are excluded the slopes are in general low, less than 8 percent, and most are between 2 and 5 percent. Agricultural lands are very rare on slopes of more than 8-12 percent and areas with over 12 percent slopes are mostly covered with forest. However, slope lengths vary, some slopes reaching a length of 1 km. Therefore, slope length is significant as a factor contributing to soil erosion.

In general, gentle slopes have greater length than steep slopes which are associated with wadi sides and usually covered with natural vegetation of forest and shrubs.

The main water divide of the Jabal determines two major drainage areas. In the northern area, runoff is discharged towards the sea by several wadis following the general slope of the land. However, most of these wadis terminate at the foot of the escarpments. The most important drainage systems are Wadi Darna and Wadi Al-Kouf (Figure 3.3). They run in opposite directions, parallel to the edge of the second escarpment, away from the high part of the second bench south of Ras al-Hilal. They both turn at right angles and descend to the sea transversely to the escarpments and benches. In the southern area, runoff is towards the desert.

No permanent rivers or streams occur in the area. The study area is, however, subject to small floods about every five years and larger floods about every ten years. In the Al-Marj basin (Figure 3.2), waters from large floods can cover a total area of up to 100 sq. km. This type of flooding is usually related to the amount of rain received in a rainfall event which can reach 100 mm in 24 hours in some exceptional cases. This amount of rain falling on relatively impermeable soils causes runoff to the wadi systems, especially from the second bench (GEFLI, 1975). In addition to Al-Marj, the first bench has several closed basins that are generally flooded during the rainy season and provide good soil and water for agriculture.

Figure 3.3 DRAINAGE AND WATER DIVIDE



Source: FAO 1969 Report to the Government of Libya on Development of Tribal Lands and Settlement Project, Rome, FAO/SF20.

3.3 Geology

Desio (1969) divided Libya into two distinct areas based on the date of emergence from the sea:

a. Northern Libya including Cyrenaica, Sirtica and Tripolitania.

b. the Libyan Sahara, which includes Fezzan and the Libyan Desert.

The Libyan Sahara was the first part to emerge at the beginning of the Mesozoic. In the Northern area Tripolitania emerged at the beginning of the Eocene, Cyrenaica and Sirtica first emerged towards the end of the Miocene, however, Cyrenaica's emergence continued into the Pliocene.

The central part of Al-Jabal Al-Akhdar was the first part to emerge in Cyrenaica at the close of the Miocene. This emerged part was then broken in the north by faults. This faulting is expressed in the topography as two steps on the northern side of Al-Jabal. Desio concluded that the relief of Cyrenaica is mainly the result of the tectonic movements that occurred between the Late Miocene and the end of the Pliocene. During the Quaternary vertical movements in sea level caused small horizontal displacements of the coast, but the geomorphic processes in this area must also have been influenced by climatic fluctuations during the Quaternary.

Different hypotheses have been put forward for the origin of the benches of northern Cyrenaica, explaining them as a result of either faulting or marine erosion. The first hypothesis attributed the sharp bends of the coast and the variations in the level of the plateau to the influence of faulting (Spratt, 1865, cited by Gregory, 1911). This explanation was confirmed by Gregory (1911), who classified these faults into three main groups. The first group trends approximately east and west to form the part of the first escarpment behind Susa and near Darna. The second trends from south-west to north-east and gives rise to the part of the second escarpment located to the south east of Al-Marj. The third group trends approximately north and south, and includes the Gobba fault, the continuation of which may form the headland of Ras El-Hilal.

Gregory suggested that these faults are not necessarily of one age, but they are probably all part of a connected series of movements. Also, because these faults occurred a long time ago the actual faults are hidden, for the escarpments have been worn back, and the fault-lines covered by talus.

The second hypothesis was that the two escarpments might be wave-cut cliffs, formed during pauses in the original uplift of the Jabal. This was first suggested by Marinelli (1920), supported later by Ahlmann (1928) and Stefanini (1930), cited by Hey (1956).

Due to the increased geological information on the area, Marchetti (1934) was able to confirm the existence of two of Gregory's faults. He also referred to two groups of faults east of Darna and northeast of Cirene. These different opinions were the basis of Desio's suggestion (1935) that the escarpments originated by faulting. Therefore, marine erosion had supposedly been confined to certain parts of the coastal plain, and had not played an important part (all references cited by Hey 1956). On the other hand, McBurney and Hey (1955) suggested that the lower escarpment was produced by marine erosion. The period of this escarpment formation was thought to have begun in earliest Pleistocene times, and no important earth movements accompanied or followed this process. Also the sea-level changes were mainly eustatic. Therefore, the first escarpment was produced by marine erosion, and the faults that coincide with it are relatively ancient, and acted as lines along which erosion was resisted (Hey 1956). Although some parts of these escarpments are associated with faults, others are not, and so Hey (1956) rejected the hypothesis of a faulting origin for these escarpments. In his opinion, the upper bench is a wave-cut platform, and the escarpment is its associated cliff. After the occurrence of marine erosion, considerable earth movements followed in which the bench was lifted to its current height (Hey, 1956).

At present it is known that several faults occur within the area, but whether two major faults follow the upper and lower escarpments is still a subject of controversy among geologists. However, most geologists have accepted the idea that the Jabal escarpments are actually fault escarpments and that the benches were formed later by processes of marine erosion (Goudarzi, 1970; Rohlich, 1980).

All the rocks exposed in Al-Jabal are sedimentary, and most are marine sediments of Upper Cretaceous and Tertiary age (Figure 3.4). More than 90 percent of all rocks are limestones and the rest are marls and dolomites. The Upper Cretaceous limestone, marl and marly limestone are the oldest known beds (found in the north-western part of the southern slope). However, in the study area the most widespread rocks are:

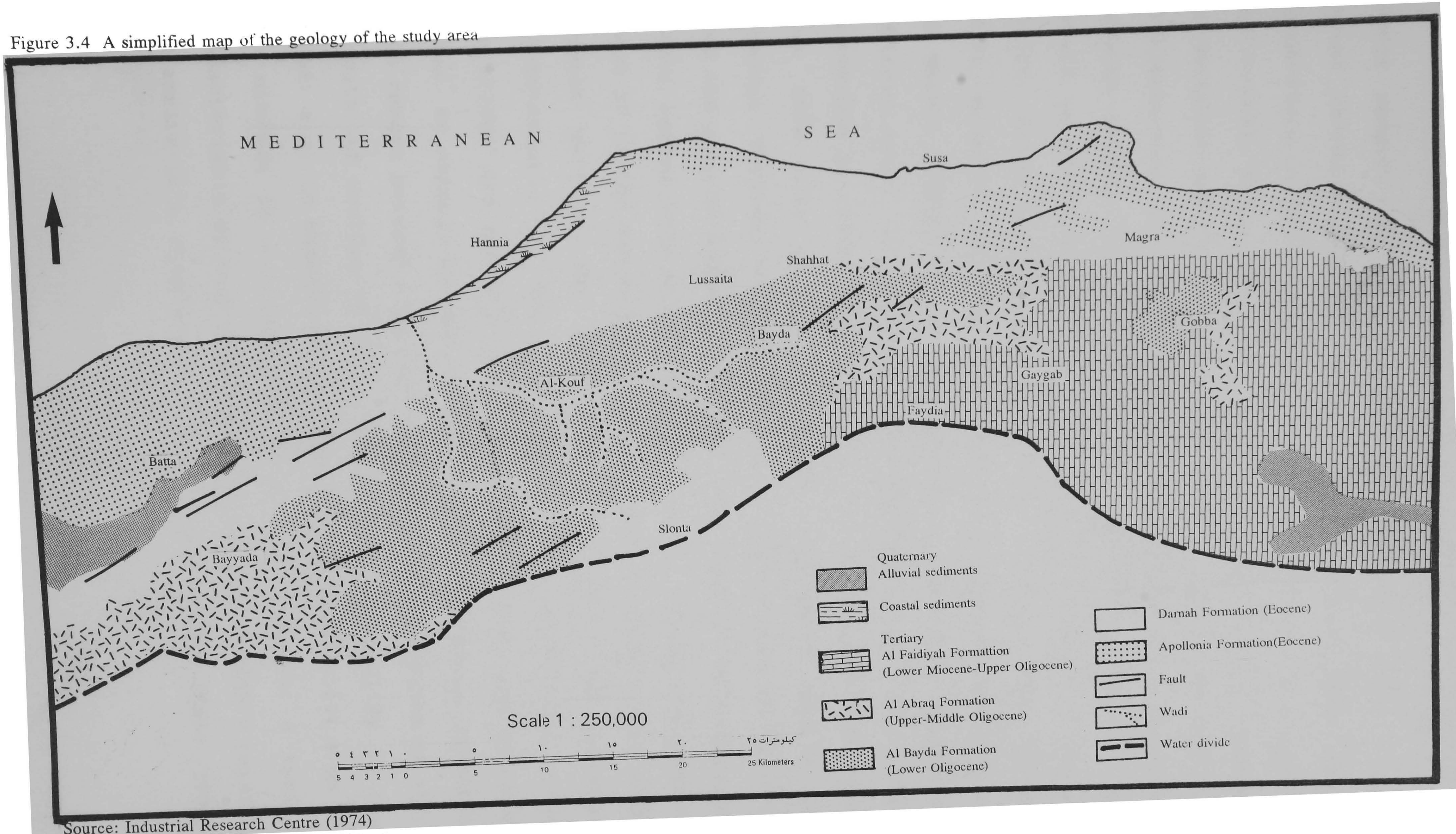
1. Eocene nummulitic limestone (known as Darnah Formation), which forms most of northern part of the first bench and some parts of the second bench, especially the Wadi Al-Kouf basin and the north and south of the town of Slonta.
2. Oligocene richly fossiliferous limestone (Al Bayda Formation) forms most of the northern part of the second bench and extending to cover some parts of the northern slope (Industrial Research Centre, 1974).

3.4 Climate

The climate of Libya varies between the Mediterranean coast and the Sahara desert, in terms of temperature and particularly precipitation. The Jabal Al-Akhdar is the wettest part of Libya, largely as a consequence of its proximity to the Mediterranean and its upland character (Allan, McLachlan and Penrose, 1973; Johnson, 1973; Kanter, 1967).

However, the climate of the area is classified as subtropical Mediterranean (FAO, 1969 and FAO, 1971). The distinctive features of this climate are a concentration of rainfall during the cool

Figure 3.4 A simplified map of the geology of the study area

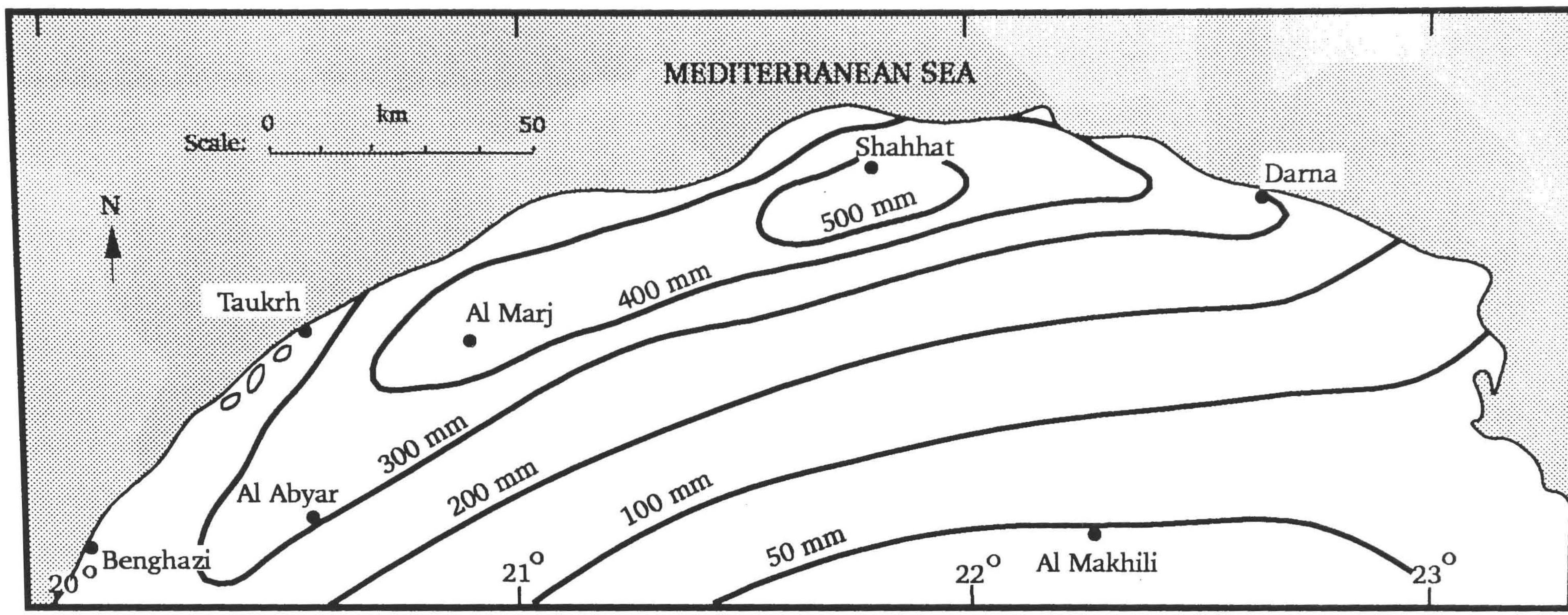


Source: Industrial Research Centre (1974)
Geological Map of Libya 1:250.000, Tripoli

winter season and a very marked summer drought. The average annual rainfall is more than 550 mm and the average annual temperature is 16°C. January is the coldest month, and August is the warmest. Rains fall from October until April, with a maximum in December and January. In the winter, air masses over the Mediterranean, an area of convergence between air of Eurasian and Saharan origin, are often rendered unstable by the sea. The result is often cyclonic precipitation, enhanced by orographic uplift, which may be intense (Allan, McLachlan and Penrose, 1973). However, there are frequently long dry spells within the wet season (Kanter, 1967). The rainfall is highest on the central northern slope, in the area around Shahhat (Figure 3.5), where it reaches an annual average of more than 550, mm then decreases from this area in all directions, especially towards the interior. However, the zone of highest rainfall does not coincide with the zone of highest elevation. The number of rainy days per season varies from an average of 70 in the 500 mm zone down to about 32 in the 300 mm zone. Snow has been known to occur in the highest part of the study area (FAO, 1969). An important characteristic of the rainfall is its variability; great variations are possible from year to year and from place to place. An example of this is Shahhat where the annual amount of rain ranges between a maximum of 870.5 mm and a minimum of 376.2 mm with an average of 568.3 mm. Monthly variability is also found: e.g. in Shahhat the maximum for December is 434.8 mm and the minimum is 8.0 mm. Even on a monthly basis, a typical characteristic of such an environment is that a month's rainfall can arrive in a single week or in a couple of days (Sala, 1988).

Figure 3.5

RAINFALL



Source: FAO 1969 Report to the Government of Libya on Development of Tribal Lands and Settlement Project, Rome, FAO/SF20

For example in December 1981 at Shahhat a total of 41.2 mm was received in 5 days, half of which fell in one day, and in January 1982 when the monthly total of 52.9 mm fell in four days and the rest of the month was dry (Chapter 5). As previously mentioned, the principal source of rainfall is from cyclonic disturbances, originating in low pressure systems in the Mediterranean basin; these cause moist air to flow into the area from the west or the north-west bringing rain. This wind shifts to the north-east during the summer months. Because of the unstable weather conditions a change in wind direction from west to south may occur. The southerly wind (called the Gihibli) is hot, extremely dry and often heavily laden with dust. Gihibli conditions can affect the coastal area at any time of the year, but generally show a maximum frequency in the spring (April, May) with a secondary maximum in October. In the latter period, when the sea is warm, they give rise to appreciable rainfall but their most pronounced effects during the spring are on temperature (Griffiths, 1972). These winds dry the soil and frequently parch the vegetation. Because of the desiccating effects of this wind, crop plants may be damaged, especially during their critical growth and development stages.

From the agricultural point of view the high elevation of the study area, and the central part in particular, give it some very important advantages over coastal areas of Libya as follows:

1. Temperatures are lower, which results in a lower evapo-transpiration rate. This makes rainfall more effective in

sustaining plant growth in this part than in areas with higher evapo-transpiration rate (Aschmann, 1973).

2. Humidity is increased by increased cloudiness.
3. Gihibli conditions are less severe at these high altitudes.

In addition, slope aspect has exerted some control on climatic conditions of the study area. As a north-facing slope in the Northern hemisphere the study area is wetter and colder than the southern slope. Moreover, the direction of the Gihibli is from the south and therefore it has a minimal effect (Besler, 1987; Breda, 1991).

3.5 Vegetation

Naveh (1986) classified Mediterranean uplands as part of the Sclerophyll Forest Zone, where broadleaved and chiefly evergreen trees and shrubs with thick but mostly leathery leaves are found. Most of these plants are characterized by dual root systems both spreading horizontally and penetrating deep into rock cracks, and an ability to withstand fire, grazing or cutting. In some regions of Mediterranean uplands such as some parts of the Jabal where mountain elevation is lower, the climate is warmer and drier, the natural vegetation has a park-like nature, dominated by scattered trees with an under storey consisting of shrubs and grass.

In the Jabal area precipitation is the main factor that determines vegetation cover and land use (Behnke, 1980). Generally precipitation increases with elevation, whereas temperature follows the opposite pattern. However, this can be modified by factors such as soil type, exposure to rain-bearing winds and distance from the sea. Three general classes of cover may be identified, however. These are from north to south: forest, steppe and desert.

In addition to climate, relief and soil type, the geographical distribution of these classes is also a direct function of cultural conditions. On the whole practices such as wood-gathering, grazing, and land clearing have tended to degrade the natural cover, resulting in a reduction of tree cover and the spread of steppe and desert conditions into some of the better-watered portions of the region.

On the basis of climate and relief Johnson (1973) divided the vegetation of the Jabal into two main types. These are maquis and steppe. Maquis, or mattoral, is a one or two-layered, closed, tall shrubland (Naveh, 1986). Maquis tends to dominate in areas where relatively large quantities of precipitation are received, especially the central part of the upper bench. On the other hand steppe vegetation is widespread in the eastern and southern parts where rainfall totals are lower (Johnson, 1973).

The maquis contains a large number of species, the most common of which are: *Ceratonia siliqua* (carob), *Olea europea* (Zaytoon), *Quercus coccifera* (Baloot) and *Juniperus phoenicia* (Shaara). These have an under-storey consisting of grass and shrubs such as *Pistacia lentiscus* (Batom), *Phlomis floccosa* (Zahayra), *Callycotome villosa* (Gandool), and *Arbutus pavari*

(Shamari). All the above are usually associated with ferrosiallitic soils. *Poterium spinosum* (Shibrig) is particularly associated with former farmland. Where soils are shallow, *Rhamnus oleoides* (Saloof), which is grazed by animals, is abundant (Soil-Ecological Expedition Report, 1980).

In more marginal areas, *Pistacia lentiscus* is a common evergreen shrub, combining low palatability and great drought resistance with vigorous regeneration powers after fire and cutting (Naveh, 1986). *Juniperus phoenicia* are widespread trees in places having lower rainfall and generally less favourable climatic conditions. Where rendzina soils dominate *Rosmarinus officinalis* (Klil) is abundant, and is associated with *Pistacia lentiscus,* Cistus, and thymes (GEFLI, 1975).

The 300 mm isohyet is the dividing line between maquis and steppe vegetation. The steppe communities are characterized by climatic conditions of lower amount of rainfall than the maquis. Species like *Zizyphus lotus* (Sidr), *Artemisia campestris, Artemisia herba-alba* (Shih) and its associates *Thymelaea hirsuta* (Mathnan) are the most abundant (Johnson, 1973). Although the sheep industry relies heavily on grain and concentrated feed for most of the year, the steppe vegetation zone is still the main grazing area for sheep.

3.6 Soils

The lime content of the sedimentary limestones of the area dissolves on weathering. The residue is a strongly calcareous clay, silty clay, clay loam or silty clay loam which forms the most important and common soil parent materials. Another important soil forming material is nummulitic limestone. Soils derived from these marly and chalky limestones containing high amounts of clay and $CaCO_3$ occupy minor areas (Hubort, 1964). Also, as limestone soils, loamy to clay texture is dominant (Jahn et al., 1989). In fact one of the most important physical properties of these soils is their clayey texture. It has been reported that clay content exceeds 50% in deep horizons in most cases and reaches 70% in some cases. On the other hand sand percentage is usually low, less than 15% (ACSAD, 1984). Table 3.1 shows the classes of soil textures which were obtained from analyzing 192 samples from the study area.

Table 3.1 Soil texture classes of the study area

soil texture class	frequency	percent
clay	57	29.69
silty clay	8	4.17
sandy clay	1	0.52
clay loam	42	21.88
silty clay loam	54	28.13
silty loam	13	6.77
loam	14	7.29
sandy clay loam	2	1.04
sandy loam	1	0.52
total	192	100

From the Roman potsherds found in the soil which fills the depressions of Al-Jabal, it has been suggested that the bulk of the soil in depressions was washed down during or after Roman times. Some of these deposits are now being gullied by the headwaters or tributaries of wadis (Vita-Finzi, 1969).

Thus, in general, the soils of the study area are developed on a highly calcareous parent material. They are shallow with Terra Rossa (ferrosiallitic red soil) predominant (Ben-Mahmood and Al-Jindeel, 1984). However, in some exceptional cases deep soil is found in isolated pockets of karst erosion and depressions or behind Roman check-dams. Such areas are usually limited and soil depth decreases rapidly from the centre towards the edges. Another characteristic of these soils is the absence of well-devolped horizons, because of either continued water erosion on slopes or continued deposition on flat and low areas (ACSAD, 1984). These soils are subject to severe cracking under summer drought conditions, so that cracks of 1 cm width and 50 cm depth can occur. This is due to the high percentage of montmorillonitic clay that the soil contains (ACSAD, 1984).

In addition to the clayey texture, subangular blocky structure is predominant in the surface horizons, and angular blocky in the deep horizons. In some few cases where soil is rich in organic matter the structure is crumb-granular. Organic matter is low, on average 1-2% in surface horizons and decreasing with depth. The levels of organic matter are highest in relatively undisturbed forest soils and lowest in soils under cultivation (ACSAD, 1984) (Chapter 6).

A definite pattern of soil types can be found along the two benches as a result of climate variations caused by differing elevations (Hubort, 1964). In addition, soil conditions can vary within a small area depending mainly upon rainfall and local topography. In the high elevation areas where the climate is more humid and cooler, a rendzina replaces the Terra Rossa on soft marly limestone.

Since Terra Rossa is the main type of soil in the study area, it is important to mention some of its characteristics and to explain some of the main processes that produce this soil. In addition to the fact that Terra Rossa is restricted to hard crystalline limestone, the climatic regime of temperate wet winter and hot dry summer is the most important factor that controls the formation of this soil. However, the basic process that produces Terra Rossa is the chemical weathering and dissolution of crystalline limestone. Dissolution is carried out during the wet season by soil water charged with carbon dioxide, taking the form of carbonic acid. This process intensifies under a vigorous vegetation cover, since the carbon dioxide content of soil moisture is primarily dependent on the vegetation and biological activity. However, the purity of the hard crystalline limestone reflects the intensity and time of weathering required to produce deep soil (Atkinson, 1969).

Decalcification, or the removal of free calcium carbonate from the soil, is a process which operates with rock weathering. Most of the Terra Rossa in the study area is free of calcium carbonate, which has been leached away (ACSAD, 1984). In some places, leaching of fine clay particles by percolating water has led to the formation of an argillic B horizon (ACSAD, 1984) This latter process, known as argillation, is one of the prime diagnostic morphological features of Terra Rossa (Atkinson, 1969). Another important characteristic of Terra Rossa is the red colour which is a result of a process known as rubefaction.

According to a previous study carried out by a French company (GEFLI, 1975), the soils of the study area can be placed in three main categories. These are as follows:

Subclass	Subgroup
1. Calcareous soils	a. rendzinas
	b. calcareous brown soils.
	c. vertic brown soils.
2. Ferrosiallitic soils	a. ferrosiallitic red soils.
	b. ,, brown soils.
3. Alluvial and colluvial deposits.	

1. Calcareous soils are characterized by having more than traces of carbonates in the fine earth in A horizon. The structure is granular or angular blocky and the pH is higher than 7.

a. Rendzinas are calcareous, calcic soils, effervesce throughout profile with cold diluted HCl, shallow, having an AC or AR profile, without B horizons. Including calcareous pebbles if the parent rock is not too friable (chalk-marl) and possessing a clearly granular or subangular structure. pH is higher than

7.

b. Brown calcareous soils: the structure of the superficial horizon of this group is granular to fine angular blocky, effervesce in B horizon with diluted HCl, and have a pH of more than 7. Deeper than rendzinas, having a distinct Bw horizon.

b1. Calcareous brown soils, as b above.

b2. Vertic brown soils, as b above but with significant cracking when dry.

2. Ferro-siallitic soils. The iron oxides accompany the clay and are distributed similarly in the profile. The profile is highly coloured. The fine earth of horizons A and B are leached of carbonates which usually accumulate in the Cca horizon.

a. Ferrosiallitic red soil. These soils are widespread on the Jabal benches as well as the coastal plain. They are formed from hard limestone, they are red in colour and are leached of $CaCO_3$. They have a clayey-loam or clayey texture. A compacted brown-red horizon is usually found at a shallow depth. Depth varies from over 1 metre in valley floors and depressions to only a few centimetres with occasional outcrops of hard limestones in others.

b. Ferrosiallitic brown soils, these are similar to red subgroup, but have a yellowish-brown colour, polyhedral structure and clayey texture with a very pronounced vertic character.

3. Colluvial and alluvial deposits. A group of soils which are moderately weathered, formed in alluvial and colluvial deposits, which range from clay to fragments of rock. These are characteristically found on wadi floors, alluvial fans and accumulated deposits on the lower parts of slopes. Being derived from the erosion of various soil types, colluvial and alluvial soils vary considerably in character. Usually however the alluvial soils in the valley floors form the thickest and most fertile soils of the region.

3.7 Land use

Libya's highest rainfall zones coincide with the study area, where some of the best agricultural lands of the country are located. Traditionally, extensive dry farming cultivation of wheat and barley and stock-herding with goats and sheep were the main activities in the Jabal Al-Akhdar (Joffe, 1989). The ancient Greek and Roman farms indicate the intensive exploitation of the agricultural resources during that period (Buru, 1989). The remains of ancient check-dams and channels indicate that during Roman times, by adopting special irrigation techniques, farming extended into drier areas than are now cultivated. Vita-Finzi (1969) suggested that the Roman period was characterised by slightly higher precipitation than is current. However, both dry cereal farming and the use of drought-resistant perennials, such as olives, grapes, and figs, were involved. Grains were planted in level land, irrigated gardens of fruit and vegetables were developed in small alluvial basins and olives and vines planted on steep lower slopes. Grazing was practised in the roughest and poorest areas (Aschmann, 1973).

The first step in the Italian colonisation was the acquisition of suitable lands for cultivation. Farms were developed in the area to produce mainly wheat, grape vines, olive and almond trees (Buru, 1989). However, this Italian extension of agriculture to areas of good grazing land forced the local people to move with their animals to the interior range, making it more liable to overgrazing, and reducing its vegetation cover. Furthermore, the increased demand for livestock in the years following oil discovery encouraged livestock breeding. The result was more pressure on the range resources and a further reduction in the vegetation cover (Allan, 1981; Benzabih, 1985).

Fruit became important during the mid-sixties, when the area was a part of a project to use the oil revenues in developing the agricultural sector through developing the existing farms and reclaiming the land for new farms. Following a soil and water survey of the area, by FAO (1969), a scheme for development based on partial irrigation was established. This involved using both existing farms and newly developed farms. The farming system is usually a combination of irrigation, semi-irrigation and dry farming. For example, a farm of 7 ha in size is divided into about 2 ha irrigated crops, 4 ha of dry farming and 1 ha of fruit trees. Each farm, or a group of farms, is supplied with a well. The water pumped from this well is then used for irrigation mainly by means of furrows (irrigation channels). Only a few farms use sprinkler or drip irrigation.

The boundary between the region where static agriculture under dry farming is possible and the region which is suitable only for semi-nomadic pastoralism is demarcated by the 300 mm isohyet (FAO, 1969).

In the 1970s, in order to achieve self-sufficiency in food, Libya increased the amount of funds allocated to the agricultural sector. Most of these funds were devoted to major development projects. The Jabal Al-Akhdar Project was one of these projects, which was aiming to introduce nomadic people to settled agriculture through developing new lands. Irrigated areas have increased since then and the result was a sharp lowering of underground water in the area (Benkhial and Bukechiem, 1989; Buckechiem and Momsen 1989). Through all the previous projects the farms varied in size from 5 ha to 80 ha based on factors such as the quality of soil, availability of water and yields.

At present, three major land uses can be distinguished: rainfed agriculture, semi-irrigated agriculture and grazing. A mixture of these is found throughout the study area.

Rainfed agriculture has long been the predominant activity in the region, and mainly involves the cultivation of wheat and barley. They are sown after the first winter rains in October or November. The yields of the two crops, and especially wheat, are totally dependent on the annual amount of rainfall and its distribution through the season. In the case of fruit trees and grapes the total amount of rainfall is more important than its seasonal distribution (FAO, 1969). The wide variations in rainfall amount and distribution make dry farming both risky and expensive (Allan, 1989). Management is largely mechanized; however, on small farms which usually occupy steep slopes, farming operations by hand are common. In addition, dry-land farming is usually supplemented by the rearing of livestock (sheep, goats and cattle).

Semi-irrigated agriculture or agriculture with supplementary irrigation is mainly focused on the production of fruit. Of these, apples and grapes are the main crops, while apricots, peaches, pears and almonds occupy minor areas. In addition to the irrigation of these trees for the first two years of plantation, they must also be irrigated a few times during the hot and dry summer months. In such cases, water must be carried by lorries, and each tree has to be irrigated separately by pouring the water to fill a small trough that surrounds the trunk of the tree.

Grazing activities usually take place in uncultivated areas of rugged terrain and poor soils that support a maquis vegetation. However, barley and wheat fields are important grazing areas after harvesting especially for sheep. Goats are generally the main animals in areas of steep slopes covered by trees and shrubs, especially on the second bench, where shrubs are the dominant vegetation. Cattle are found in flat areas such as valley floors and the coastal plain.

3.8 The soil erosion problem in the study area

Water erosion arises when rainfall does not all penetrate the soil because rainfall intensity is greater than infiltration capacity of soil or the soil is saturated. When not protected by adequate vegetation, the excess runs off the land, carrying with it detached soil particles. The detached material is usually the topsoil where plant nutrients are most heavily concentrated. The amount of overland flow is decreased by increasing coverage of vegetation. The protective role of vegetation cover can be illustrated by the interception of a large proportion of the kinetic energy of rain drops. In addition, the root systems developed by vegetation increase the porosity of the upper horizons of soil and hence increase its infiltrability. Water erosion is a normal sub-aerial geomorphic process; however when soils are cultivated or vegetation is removed the process is accelerated, greatly increasing soil loss and accumulation of sediment (Bufalo & Nahon, 1992).

The northern slope of Al-Jabal Al-Akhdar experiences some of the most severe natural soil erosion effects in Libya. This is because first, in addition, to the relatively high quantity of rainfall, this area is characterized by lower temperatures resulting in lower evapotranspiration rates. Secondly, humidity is further increased by higher cloudiness and occasional heavy morning fog during the summer and also by less pronounced Gihibli conditions (FAO, 1969). These two factors combine to increase the amount of water available for runoff, even though the increased moisture improves vegetation cover. Thus, these wetter conditions, when combined with agricultural activities which clear vegetation, almost inevitably lead to serious accelerated erosion especially on the steeper slopes. Although all types of water erosion, splash, sheet, rill and gully erosion, are found in the study area, sheet and rill types are considered very dangerous because they are not always obvious until all of the topsoil is gone.

Chapter 4

Methodology

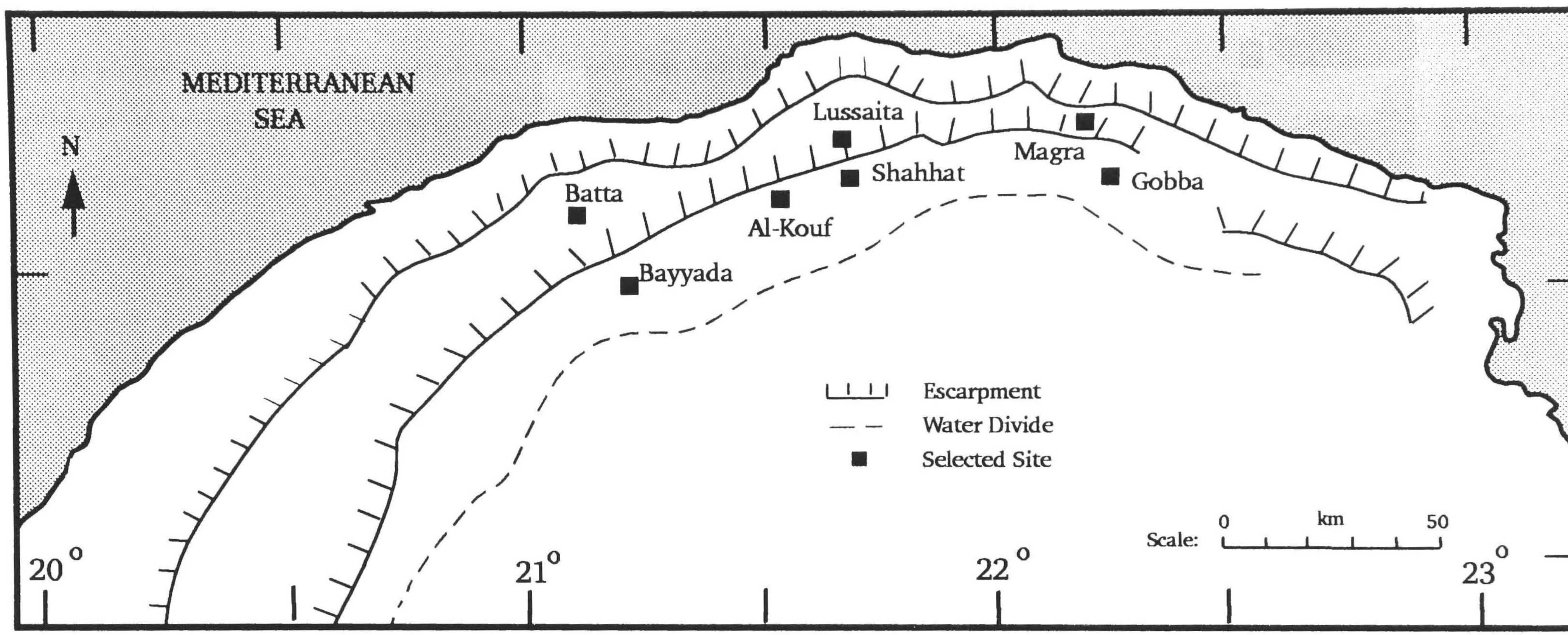
4.1 Introduction

Because of the variability of climate, especially rainfall, reflecting the differences in altitude and topography on the northern slope of Al-Jabal, the study of this area must take into consideration the differences between eastern, central and western parts of the lower and upper benches. Therefore, it was suggested that in order to represent the whole area the eastern, western and central part of each bench has to be represented. Furthermore, in selecting representative sites it was considered of particular importance to have a weather station or a rain-gauging station located in the site or in its vicinity.

4.2 Selection of representative sites

By using a map at a 1:250,000 scale, eight sites were found to meet the previous conditions. However, after a pilot visit to these eight sites, it became evident that additional factors had to be taken into consideration before a final choice of study sites was made. These conditions were: inclusion of the main soil types, vegetation and land use and ready accessibility by car. From these eight initially identified sites six were found to be broadly representative of the range of conditions found in the study area and appropriate for the study of water erosion. The sites selected are: Gobba, Shahhat, Bayyada, Magra, Lussaita and Batta (Figure 4.1). Al-Kouf, a seventh site, was used for erosion measurements (section 4.7). The sites selected on the first bench from east to west are Magra, Lussaita and Batta; and on the second bench Gobba, Shahhat and Bayyada.

Figure 4.1 LOCATION OF THE SELECTED SITES



Source: Libyan National Atlas (1978)

4.2.1 Selection of representative slopes

Having selected the study sites, a preliminary study to select the slope profiles in each site was made, based on the interpretation of topographical maps at a scale of 1:50,000. Following this, a reconnaissance was carried out to inspect the variety of hillslopes occurring in each site in order to check the suitability of site selections made from the topographic maps, and to find a source of water for infiltration rate measurements. Slopes with approximately straight contours, simple profiles and having different aspects and land uses were selected for survey. Furthermore, in each site slopes were selected to represent the variety of slopes in that site in terms of slope length and steepness. Each profile was marked at both ends. A sketch map of the general location of each slope was included (Appendix 1). A description of the slope was produced, dealing with the general nature of its topography, the presence or absence of erosion features, the nature of its base level, and the general character of its vegetation cover and surficial material.

4.3 Data collection

4.3.1 Information required for this study

Since this study is aiming to obtain information required to develop appropriate measures to minimize the loss of soil, an assessment of the factors that influence soil erosion in the area was needed. These factors are: soil erodibility, topography, rainfall erosivity, land use and vegetation cover. To assess the relative importance of these factors the following methods were adopted.

4.4 Methods

4.4.1 Slope profile surveying

The method used to survey slope profiles in the field was the clinometer and tape method (Herweijer, 1984; Young <u>et al.</u>, 1974). This method is based on measuring angles by clinometer, and distances by tape (Plate 4.1).

Plate 4.1 Slope profile survey.

According to Young *et al.* (1974) there are two methods of surveying slope profile. These are:

1. Standard measured lengths, where a length of 2, 5, 10 or 20 metres can be used depending on the conditions of the slope. Therefore it is recommended that the selection of a suitable length should be based on a pilot study of the investigated area. However, a problem in selecting a standard length that fits all portions of slope is always raised. Short lengths are usually appropriate for portions of slope that are variable so detail will not be lost. On the other hand, long lengths are only suitable for surveying uniform portions. In addition, in surveying a slope profile a longer time is required by adopting this method. In general, this method is suited to specialized surveys where high accuracy over short distances is necessary, e.g. studies of microrelief.
2. Variable measured lengths, where a station is located where a break in slope or change in angle occurs.

In this study, the variable length method was found to be suitable since the time for the field survey was limited and most of the slopes are regular and simple.

Each profile was surveyed from the local base level to the upper end, which is the local water divide. Distances and angles for each station were recorded on a prepared form (see Figure 4.2 for an example) and the bearing for each profile was measured with a Brunton compass.

Figure 4.2 An example of slope profile survey sheet.

Site. Lussaita

Slope profile No. 1

Bearing. 270°

If the slope terminated into a channel, channel width (m). 4

S.	G.	D.	S.	G.	D.	S.	G.	D.
1	27	6	11	12	20			
2	6	35	12	15	17			
3	8	66	13	9	20			
4	30	2	14	2	15			
5	9	11						
6	23	4						
7	9	38						
8	30	3						
9	8	41						
10	9	37						

S=station no. G=gradient (degrees) D=distance (metres)

offset.

station	12	13				
direction	left	left				
distance (m)	3	4.5				

Notes.

1. valley side slope.
2. from station 11 to station 14, the slope is covered by a dense cover of natural vegetation.

4.4.2 Cross profile surveying

On each profile three locations were chosen for a detailed cross profile survey. Each cross profile was located approximately on the centre of the lower, middle and upper parts of the slope. The distance between the location of each cross profile and the starting point was recorded. The cross profiles were surveyed during the measurement of the main profile. Cross profile surveying was obtained by laying a tape at right angles to the line of the profile. Each cross profile was 10 metres long divided into 20 parts, each 0.5 m long. At each cross profile measurements were made of soil thickness, vegetation, stones, rock outcrop cover and infiltration rate and recorded on a form (Figure 4.3 shows an example). Two soil samples were taken from the top 15 to 20 cm of the soil to determine the texture and organic matter for each cross profile. One of these samples was located about 0.5 m on the left and the other also about 0.5 m on the right of the point where the cross profile meets the slope profile. These samples were collected by digging a hole of about 15 to 20 cm in depth; about 1.0 kg of soil was then taken from a vertical line from the soil surface to the bottom of the hole in order to obtain a representative sample.

4.4.3 Soil properties

Soil erodibility is mainly a function of its physical and chemical properties, (Holy, 1980; Jaiyeoba and Ologe, 1990; Kirby and Meyhuys, 1987; Morgan, 1986; Wischmeier, 1977). Wischmeier et al. (1971) determined the K factor from particle-size distribution, organic matter content, structure and permeability.

Figure 4.3 Example of a cross profile survey sheet.

Site. Lussaita

Slope profile No. 1

Cross profile No. 3

Distance from starting point (m). 236

Slope position. upper

Section 1. Soil depth (cm).

augering No.	1	2	3	4	5	average
soil depth (cm)	15	17	16	21	30	19.8

Section 2. Topsoil properties.

soil texture	OM (%)	OC (%)	IR (cm hr^{-1})
clay loam	3.6	1.8	7.0

Section 3. Bare ground and vegetation cover.

veget. type	shrubs	trees	grass	cereal	b/grd	others
No. of c.p. parts covered	8	4	0	0	3	0

Section 4. Stone cover and outcrop exposure.

type of cover	stones	outcrop exposure
no. of c.p. parts covered	5	0

OM=organic matter OC=organic carbon IR=infiltration rate
b/grd=bare ground c.p.=cross profile

These different studies agree that the most significant soil properties in determining soil erodibility are those can affect the infiltration of precipitation into the soil such as structure, texture and humus content. Therefore, in order to determine soil erodibility in the study area the following properties of organic matter content, texture, structure and infiltration rate were determined for the top 20 cm of the soil profile.

Observations were carried out by auger in addition to road cuts and quarries to determine soil depth and the existence of an impermeable layer. The measurement of soil depth is aimed at correlating soil depth with position on slope and vegetation cover. Also, if soil depth increases in the downslope direction,infiltration rate might increase and this in turn will offset the effects of increased runoff in the downslope direction, a common condition in arid and semi-arid environments (Thornes, 1990).

4.4.3.1 Field measurements

1. Soil depth measurements were made at right angles to the soil surface by augering (Reynolds et al.,1975). Five measurements were made in each cross profile and the soil depth for the site was taken as the average of the five measurements (Carson, 1967). Two measurements of soil thickness were made at the two ends of the cross profile and the other three measurements were distributed along the cross profile with five parts of the cross profile, a distance of

approximately 2.5 m separating each (Plate 4.2).

Plate 4.2 Cross profile survey, mesuring soil depth by auger.

2. Infiltration rate was defined by Kirkby (1969a) as the maximum rate at which water can penetrate into the soil. According to Hills (1970), infiltration refers to the vertical entry of

water into a soil surface. Infiltration rate is a measure of the quantity of water infiltrated per unit time.

Infiltration rate in this study was determined by observing the fall of water within two concentric cylinders driven vertically into the soil surface layer to approximately 7 cm depth (Plate 4.3). This depth was used to minimise soil disturbance during emplacement especially where the surface was stony or where a surface crust was found. In addition to minimizing soil disturbance, this depth also allows the air to move freely laterally and escape upwards outside the cylinder (Hills, 1970). The diameter of the outer cylinder was 30 cm and of the inner cylinder 15 cm. Each cylinder location was pre-wetted for approximately one hour before starting the measurement. This procedure was used to facilitate cylinder insertion (Landon, 1984). A brief description was made of each cylinder location in terms of factors that can affect infiltration rate, such as vegetation cover, the existence of surface crust, stones, cracks, soil compaction and whether the soil was cultivated or bare.

The basic infiltration rate for each cross profile was the relatively constant infiltration rate that developed after 2 to 3 hours of infiltration. The level of the water in the cylinders was measured after 2, 3, 5, 10, 20, 30, 40, 50, 60, 75, 90, 105, 120 min and the readings were recorded on a standard form (Figure 4.4) (Landon, 1984). One measurement of infiltration rate was made on each cross profile. The location of the cylinder was, in most cases, in the meeting point of the cross profile and slope profile. However, infiltration rate measurements were not made for some sites because they were not accessible through difficult terrain, slope steepness or dense vegetation.

Plate 4.3 Measuring infiltration rate by double cylinder ring.

4.4.3.2 Laboratory analyses

1. The samples collected in the field were taken to the Department of Soil at the University of Omar Mukhtar at Bayda. Once in the laboratory the samples were air dried and seived through a 2 mm mesh sieve.
2. Particle-size analysis (PSA) is a measurement of the size distribution of individual particles in a soil sample. The

major features of PSA are the destruction or dispersion of soil aggregates into discrete units and the separation of particles according to size limits by sieving and sedimentation (Gee & Bauder, 1986).

In this study a modification of the Bouyoucos hydrometer method (1934) was used. This involved a rapid analysis using readings at 40 s and 2 hr to determine the USDA sand, silt and clay in the percentage. This method slightly overestimates the per cent of clay in the sample.

3. It is known that soil organic matter influences many soil properties. These properties include infiltration and retention of water and degree of aggregation and overall structure that affect air and water relationships (Campbell, 1978). It has also been suggested that calcareous soils tend to be deficient in organic matter. This is because when calcium carbonate becomes a dominant constituent the texture is very open and excessive aeration is further accentuated by the tendency to shallowness (Robinson, 1932). In the study area organic matter content was determined by sampling the top layer of each cross profile. The organic matter is defined as the organic materials that accompany soil particles through a 2 mm sieve.

Organic carbon is the chief element present in soil organic matter, comprising 48 to 58% of the total weight. Therefore, organic C determinations are often used as the basis for

Figure 4.4 An example of infiltration rate measurement logging sheet.

Site. Shahhat

Slope profile No. 3

Cross profile No. 2 Position. middle

Soil surface conditions: crusted.**X**., cracked.**X**., cultivated.**X**.

others ....

intervals (mins)	depth of water in cylinder (cm)	intake (cm)
0	30	
2	29.6	
3	29	
5	28.1	
10	26.4	
10	24.8	
10	23.3	
10	22	
10	20.8	
15	19.6	
15	17.7	
15	15.9	
15	14.2	
20	12	
20	9.9	
20	7.8	
20	5.7	
20	-	
20	-	
	mean infiltration rate cm hr^{-1}	**6.3**

organic matter estimates through multiplying the organic C value by a factor. The ratio of organic matter to organic C is variable from one soil to another and with depth in the profile. However, in the case of estimating organic matter content of surface soils a factor of 2 is accepted (Nelson and Sommer, 1982).

The walkley and Black (1934) wet oxidation procedure was used to determine the organic carbon content on samples of soil sieved through a 0.5 mm sieve. The resultant % organic carbon figure obtained was multiplied by the conversion factor of 2 to give % organic matter.

4.4.4 Vegetation cover, crop residues and stones

Leopold and Dunne (1971) suggested that in studying hillslope erosion in semi-arid environments the crown density of plants is the most important character to be measured because of its protective role against the impact of rain drops. However, in the study area most of the trees and shrubs were of a small size, therefore, crown density for each tree or shrub was estimated to be one part (0.5 metre) of the cross profile except in some few cases where large trees were encountered and estimated to be more than one part. Grass, plant residue from wheat and barley, bare ground and stone cover were measured directly by counting the number of parts of the cross profile that were covered by each. The total cover percentage for each cross profile was then computed for each cover type. The outcrop coverage was obtained by direct measurement of the exposed part to find the number of parts of the cross profile that were covered.

However, the per cent cover can be compared with that estimated from the cross-profile measurements. For each cross-profile, the lengths covered by bare ground, stones and exposed outcrop can subtracted from the total length of 20, and converted to a percentage. The result has a mean of 31.7%, which matches well the mean for the percent cover of 32.0%. In addition, the greater variability of the cross-profile measure, with a standard deviation of 18.9% as compared with 13.9%, bears out the expectation that a measure based on local observations should be more variable than percent cover, which is based on an assessment of the cover of each part of the profile (Melton, 1957).

4.5 Definitions and recording of soil erosion features produced by water

During the field study, some erosional features were measured or recorded along the cross profile or in the area immediately surrounding the slope profile. These features were evidence of accelerated removal of material as a result of erosion processes. However, to ensure correct identification, a definition for each feature was needed. The definitions used were adopted from different studies and they are as follows.

1. Sheet erosion.
2. Rills.
3. Concentrated flow.
4. Gullies.
5. Crusts and compaction.

6. Other features.

1. Sheet erosion is the removal of a fairly uniform layer or thickness of soil material from the land surface by the action of rainfall and runoff (Baur, 1952, cited by Savat and De Ploey, 1982; Morgan, 1986).
2. Rills usually develop when the overland flow changes into a braided pattern due to the surface irregularities and is concentrated into small parallel channels running down the slope. These channels usually do not extend back to the water divide (Finkel, 1986). Therefore, the removal of soil takes the form of shallow channels that can be smoothed out completely by cultivation (Baur, 1952). According to Foster _et al._ (1985), rills are small channels, usually about 100-300 mm wide by 50-150 mm deep, uniformly distributed across the slope. Hanvey _et al._ (1990) described rills generated in sub-tropical coastal dunes as having a depth of 0.5 m and a width of 0.3 m. They are a common feature on hillslopes with little or no vegetation cover. However, rill erosion tends to smooth out the regular profile of a ploughed field into a smoother, convex-concave form (Kirkby, 1969b).

Most of the definitions of rills agree that they are a seasonal phenomenon destroyed by ordinary tillage or by surface wash. Also, most are discontinuous, or have no connection with the main valley (Morgan, 1986). However, it has also been reported in different studies that the critical slope angle for the generation of rills is between 2° and 3°. On these slopes rills generally entrench to a limited depth of several decimetres (Savat and De Ploey, 1982). Although rills are usually regarded as temporary phenomena which either are destroyed by a variety of processes or develop into gullies, under suitable conditions they may be of a more permanent nature (Hanvey et al., 1990; Savat and De Ploey, 1982).

In the study area, the conditions necessary for rill initiation, such as soil texture, slope angles and absence of vegetation cover, are found in some localities. Therefore, the area is classified as generally susceptible to rill erosion (Plate 4.4). However, rills were not a common phenomenon. It is thought that rills were absent because the time of survey was the beginning of the winter season: even if there were rills during the last winter they must have been obliterated during land preparation for the new season, and the rain of the new season had not yet started for new rills to develop. Hence few rills were recorded during the field survey and all were less than 30 cm in depth and 15 cm in width.

3. According to Foster et al. (1985), on some landscapes overland flow converges in a few major channels, called concentrated flow. Most runoff leaves fields through this type of channel (Plate 4.5). The main characteristics of a concentrated flow channel are its width (usually few metres) and shallowness, sufficiently shallow that they can be tilled across. In comparing rills with concentrated flow channels, Foster et al. (1985) stated that the removal of a single rill will have

Plate 4.4 Rills developed on upper slopes where ploughing is in the slope direction, Batta site.

Plate 4.5 Concentrated flow erosion on upper slope area, Magra site.

little effect on the hydrologic and erosional responses; however, a noticeable effect will result from removal of concentrated flow.

4. Gullies are defined from an agronomic point of view as obstacles to farm machinery, too deep to be obliterated by ordinary tillage (Bradford and Piest, 1980; Foster et al., 1985; Poesen and Groves, 1990). Furthermore, gullies are relatively permanent features, often U-or V-shaped in cross section and steep-sided, transmitting ephemeral flow. Typically, a gully has a fairly smooth concave upwards long-profile with a single headcut or several headcuts and various knick-points along its course (Bradford and Piest, 1980; De Ploey, 1974; Morgan, 1986).

A gully can be initiated when water flows over a hillside, and forms a channel linking the small depressions, especially on an unvegetated hillslope. Therefore, gullies are not generated on sites that support a dense vegetation cover except where they invade from adjacent land (Heede, 1974). Sometimes a gully is formed as a result of a rill enlargement (Morgan, 1986). However, water that is infiltrating and moving downslope can cause chemical erosion, piping, and mass movements, such as land sliding. This can intiate gully formation, without any previous rilling, and gully head and gully side retreats (Bocco and Gracia-Oliva, 1992). It has been reported that gullies often generate on land with a minimum slope of 12° to 16° (Savat and De Ploey, 1982).

According to Brice (1966), cited by Heede (1974), gullies could be classified into continuous and discontinuous. Continuous gullies begin their downstream course with many small rills, while discontinuous gullies start with an abrupt headcut with a plunge pool located below the lip of the headcut. The pools along one channel tend to become longer as a result of flow and transporting capacity increasing down-channel. Eventually these pools coalesce and the channel becomes a continuous one (Kirkby, 1990). Bradford and Piest (1980) classified gullies into three types on the basis of topographic location.

a. Valley-bottom gullies are characterized by near vertical headwalls, and vertical sidewalls for the plunge pool area.
b. A valley-head gully is usually generated when the head of scarp of a valley-bottom migrates towards the valley head.
c. Valley-side gullies usually result from less concentrated flow coming from various directions.

Rowntree (1991) divided the channels in her study area into two groups: (1) river channels, which are related to the valley bottom drainage lines and carry alluvial material as bed load. (2) gullies, which are located on the valley sides and have channels generally free of sediments. In addition, Hanvey et al. (1990) described steep V-shaped gullies as having lengths from 5 to 60 m; widths from 0.2 to 10 m, and depth ranges between 0.1 and 16 m.

Imeson et al. (1982) classified gullies according to the erosion processes responsible for their development, the materials in which the gullies are formed and their position in the landscape. Thus the following gully types were noted:

1. V-shaped gullies on moderate to steep slopes with non-saline/non-sodic soils.
2. U-shaped gullies in marine sediments.
3. U-shaped gullies formed by piping in wadi sediments.

The area studied by Imeson et al. (1982) was located in the Rif Mountains of northeast Morocco, which is similar in many aspects to the northern slope of Al-Jabal. In addition to the similarity in climate, both areas have soils with textures in the clay, clay loam and loam classes. However, the gullies of Al-Jabal are generally of the U-shaped and valley bottom types. Also, in all the six areas no gullies formed by piping were noticed.

In the study area gully development is associated with valley-bottom and flat-bottomed depressions, where some well-developed continuous gully systems are found, especially in Lussaita, Bayyada and Batta sites. U-shaped cross-sections and steep sides are predominant characteristics (Plate 4.6). Some of them were formed as a result of enlargement of rills or concentrated flow channels, such as profile 9, Batta site, and others as a result of water concentration on areas lacking in vegetation, e.g. profile 3, Shahhat site. In such cases the gully head is usually characterized by a vertical scarp which collapses and retreats

Plate 4.6 An example of U-shaped valley floor gullies, Lussaita site.

upward as a result of water erosion at its base. In addition all appeared to be the result of a runoff increase caused by alterations in land use (clearing of vegetation). Some of the large gullies were located in wheat or barley fields in valley bottoms or depressions (Lussaita and Batta sites), perhaps due to the combined effect of the first rain of the season and the ineffective vegetation cover. The upper part of some gullies is in the form of three or four parallel channels of moderate width (3 metres in some cases such as profile 7 Batta site), and small depth (less than 30 cm). However, the real gully starts when these channels coalesce to form one main channel. In addition, some small and less developed gullies were found in different topographic positions such as the upper position of profile 4, Magra site.

From field observation, it was assumed that gullying is active in some parts. However, the development of new gullies and the enlargement of the old ones seems to be a recent event, coinciding with the recent and active transformation in the last 30 years of new areas into agricultural lands after clearing of vegetation. In addition, road construction in the new agricultural lands and fence-building have contributed to the appearance of new gullies and enlargement of old ones (profile 7 Bayyada site and profile 10 Magra site).

5. Soil crusting and soil compaction were recorded as signs of low infiltration rate, increased surface runoff and hence erosion (Bradford et al., 1987a; Mitchell, 1990). Although lacking in Gobba and most Shahhat sites, soil crusting and compaction were recorded in most sites of the remaining four areas, particularly in Bayyada and Magra sites.

6. Some less important features were also recorded in some localities. These are:

a. tree root exposure is a sign of removal of part of the top soil by water.

b. biological activity is considered to play an important part in increasing organic matter content and improving soil structure and infiltration rate. Biological activity observed included spiders, ants, worms and moles. Moles in particular were active in cultivated lands.

c. farming practice, which referred mainly to the direction of ploughing and is recorded only when the ploughing is up and down slope which would accelerate erosion.

d. cracks were recorded as local site characteristics, since their presence can affect the infiltration rate and contribute to gully development (Poesen and Groves, 1990). Cracking during the dry season is one of the main characteristics of the soils of the study area and has been attributed to high clay contents (ACSAD, 1984).The Gobba site and most slope positions of Shahhat site were the most affected by cracks and were where the deepest and widest cracks were recorded. In the Gobba site tens of almond trees were dead because their roots were cut as a result of soil shrinking. Furthermore, these cracks are obvious on the soil surface in Gobba and Shahhat sites, but they also occur at depth, especially in cultivated places and where red soils are the predominant type in Magra, Lussaita and Bayyada sites. In Magra, Lussaita and Bayyada sites, finding a place free of cracks to measure infiltration rate was a difficult task. However, as far as soil erosion is concerned, cracks are considered to be important because of their role in absorbing water. Therefore, they contribute to runoff prevention, at least in the beginning of the rainy season.

4.6 Features of soil erosion

Indications of accelerated removal of soil as a result of water erosion processes along the slope profile and in the area surrounding the cross profile were recorded. Indications like concentrated flow, root exposure or rills were recorded. Gully lengths were measured and recorded directly. Gully widths and depths were recorded as averages obtained by measuring width and depth along each gully at intervals of 10 metres: the total of these readings was thus divided by the number of measurements. Indications of biological and human activity, in particular management practices such as ploughing, were recorded during survey of the cross profile.

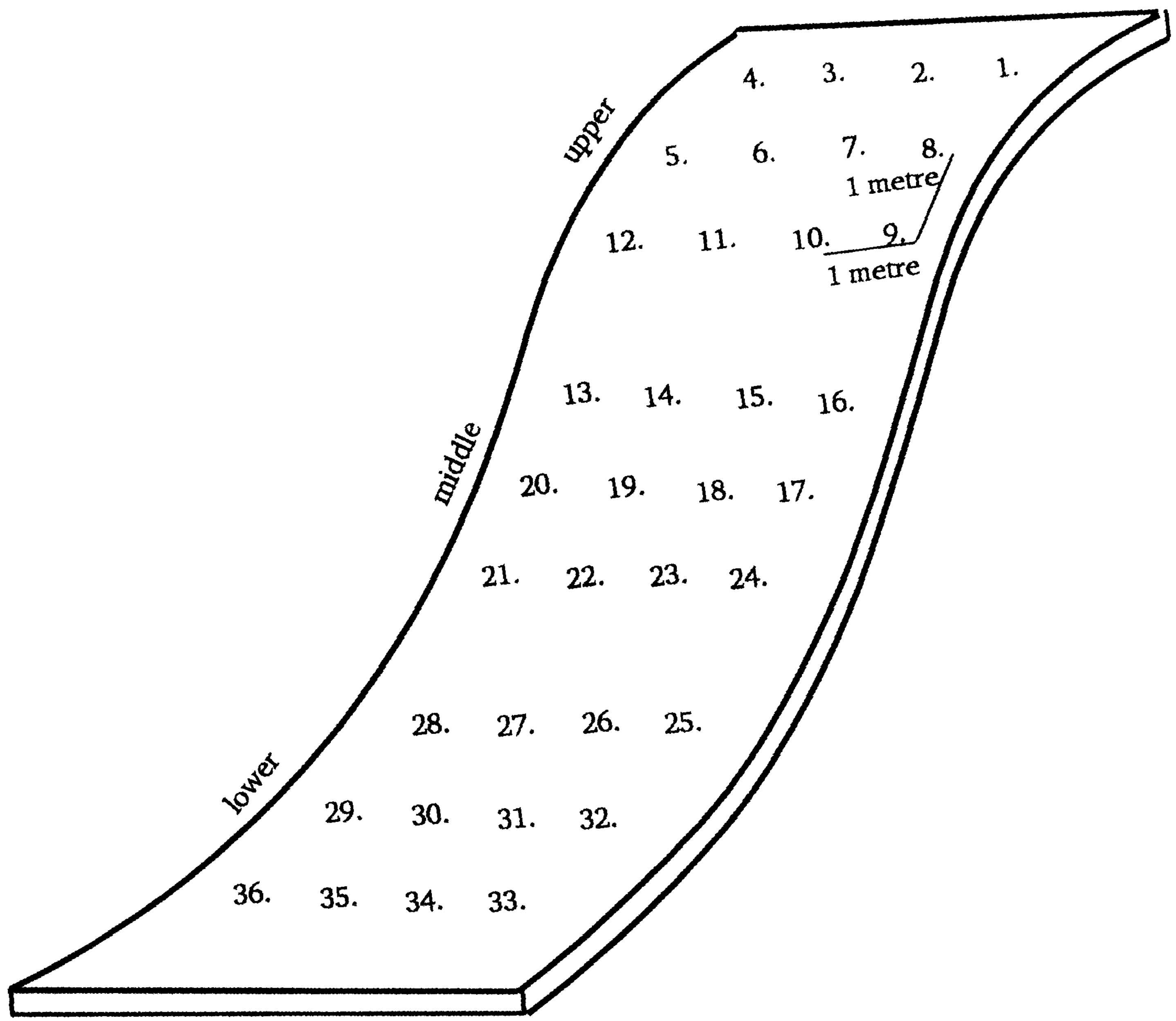
4.7 Soil loss measurements

The aim of soil erosion measurements is to assess the quantity of soil that is moved in a given space over a certain distance during a specific period of time (De Ploey and Gabriels, 1980).

In locating sites for soil erosion measurements for this study, some conditions had to be taken into consideration. In addition to the conditions considered in selecting the six areas, some kind of guarantee that the pin sites would be safe was very important. All of the six areas were suitable for pin installation but none of the farmers would guarantee that the sites would be safe. Therefore, a seventh area had to be selected and this was Al-Kouf National Park (Figure 4.1). It is located on the second bench about 25 km west of Shahhat and 30 km north east of Bayyada. Four slopes located near the rain-gauging station of Kouf National Park were selected in order to quantify the average annual erosion in the study area. The area is cultivated with winter cereal (wheat and barley) or covered with natural vegetation. These slopes were put into two groups according to their steepness and type of land use. One group comprised two steep slopes, one has a vegetation cover, while the other is bare ground. The second group consisted of two gentle slopes, one with vegetation and the other lacking vegetation. The rest of the factors that cause soil erosion like soil type, slope length and aspect and rainfall quantity were considered to be similar for all the four slopes. These slopes were monitored over a six month period during the rainy season of 1992-93.

Soil transported by surface wash processes was measured by means of erosion pins. Iron pins of 6 mm in diameter and 40 cm long were used. This length is enough for the pins to be firmly fixed in the ground and not subject to surface creep. Also, the pin's thickness will not alter the local stream and erosion pattern (De Ploey and Gabriels, 1980). The exposed part for each pin was 2.5 cm and a removable washer was used during the recording. The recording was simply by direct measurement of the distance separating the head of the pin from the washer. Twelve pins were established on each part of each slope (Figure 4.5). These pins for each part of the slope were installed in three parallel rows at right angles to the slope profile with a

Figure 4.5 A diagram illustrating the installation of the erosion pins on the monitored slopes



distance of one metre separating each pin (Haigh, 1977). To avoid disturbance and erosion caused by the act of recording, a time interval of one month was used. The first reading was recorded on 1/11/1992, when pins were established, the second was taken on 30/11/1992, and repeated on the last day of each month until 30/4/1993.

4.8. Geology

Geological information on the study area was collected from different studies and reports. In addition to studies like those of Desio (1938), the recent study made by the Centre of Industrial Research producing the geological map at a scale of 1:250,000, Sheet/Bayda, was the main source of geological data (Figure 3.4).

4.9 Climatic data

Climatic data, for rainfall in particular, were collected from the weather and rain-gauging stations in the study area. At these stations records of varying number of years, ranging between 10 and 48 years, were collected. One main weather station (Shahhat weather station) that is located in Shahhat site was considered the main source of this data. The rest are rain-gauging stations keeping records of monthly rainfall amount. Besides Shahhat site, the sites of Gobba, Bayyada, and Batta have rain-gauging stations. However, Magra and Lussaita sites, located on the first bench, both lack rain-gauging stations. To solve this problem records from Susa, which is a coastal station located 8 km northeast of Lussaita site, and the Bayda station, located on the second bench 7 km south of Lussaita, were collected. By comparing these records an average of rainfall can be determined for the Lussaita site. The same procedure was used for Magra site by using the records of Susa, located 20 km to the northwest, and the records of Gobba, located 10 km to the southwest on the second bench. Further rainfall data were collected from six other stations located within the study area. The records cover all or part of the period from 1945 to 1993. In addition daily amounts of rainfall for the six sites were collected for the rainy seasons of 1981-82 and 1981-93 for Shahhat. For the site of Al-Kouf National Park where the instrumented sites are located, a rain-gauging station was found and its records were used in studying the relation between rainfall and soil loss.

4.10 Data analysis

Stata, a statistical program, was used for graphics and data analysis. The slope profiles and associated measures were calculated from the surveyed lengths and angles using programs written in the Awk language, by Dr N.J.Cox.

Chapter 5

Rainfall analyses

5.1 Introduction

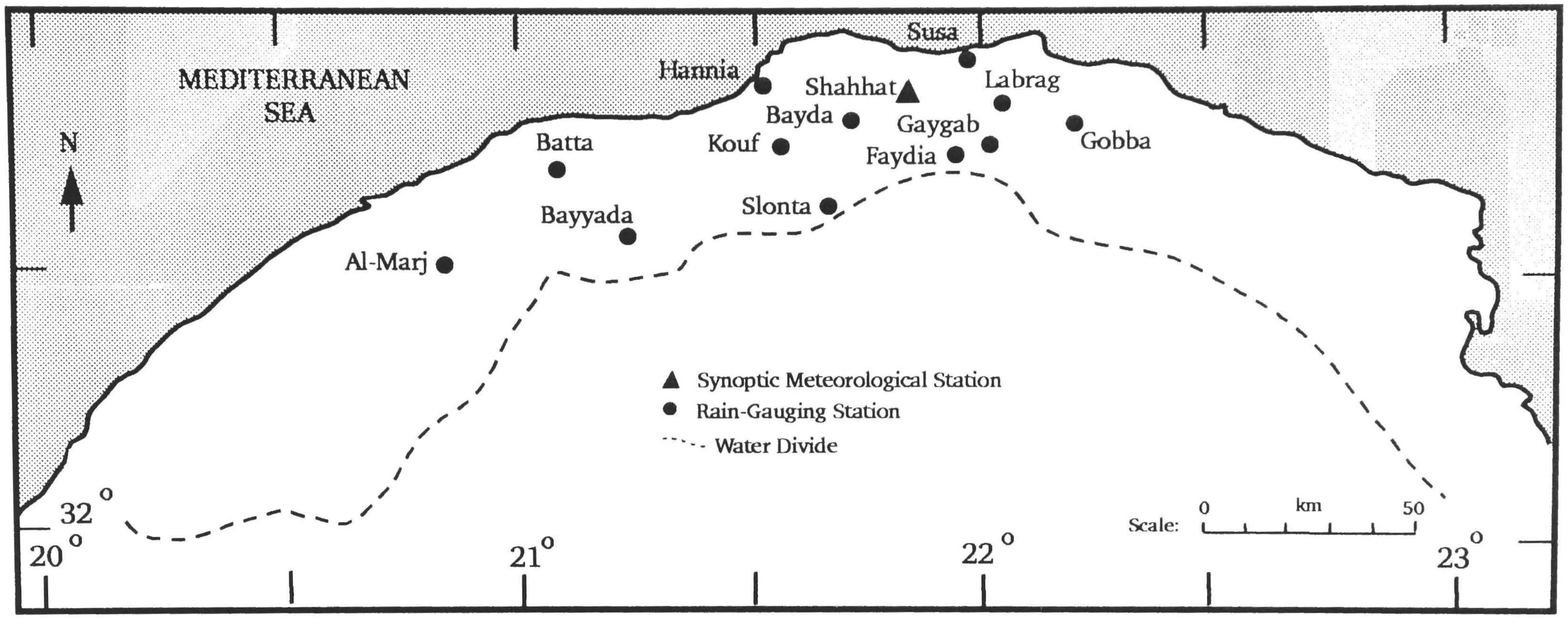
Rainfall data are of fundamental importance, actually or potentially, for several reasons:

1. as an indication of a major aspect of local and regional climate;
2. for planning civil engineering works;
3. for planning water management and conservation, particularly important in the study area, where rainfall is the only source of water;
4. for the study of crop production, agricultural conservation and land use capability. Generally, the unreliability and absence of rainfall has always been the major constraint of farming in Libya (Allan 1981).
5. for the study of soil erosion hazard and the planning of soil control measures, which is the main concern of this thesis.

The rainfall data for the study area were collected from one synoptic station and 12 rain-gauging stations (Figure 5.1). The synoptic station, which is at Shahhat, provides full observation and registration of meteorological factors such as air temperature, humidity and rainfall etc. The rain-gauging stations record only rainfall.

The Meteorological Department of the Secretariat of Communication (based at Tripoli) is the main authority responsible for climatic observations throughout Libya, and from whom climatic data records are available. However, in this

Figure 5.1 LOCATION OF METEOROLOGICAL STATIONS



Source: Meteorological Department Tripoli, Libya.

study some data, in particular those for 1991-93, were collected directly from the stations.

The stations from which records have been obtained were selected so as to provide a representative cover of the wide range of rainfall conditions experienced across the study area. The thirteen selected stations range from a few metres above sea level at Susa to 800 m above sea level at Slonta (Table 5.1), and their duration of records vary from 10 and 48 years.

Table 5.1 Location, record length and number of complete years for each station.

station	longi. deg. E	lati. deg. N	alti. (m)	d.f.c. (km)	l.o.r. years	complete years
Shahhat	21.86	32.83	621	9.5	1945-93	48
Bayda	21.75	32.76	602	19	1958-90	32
Batta	21.11	32.66	320	12.8	1965-90	10
Al-Kouf	21.56	32.72	451	17.5	1980-93	11
Gobba	22.25	32.75	595	12.5	1958-90	32
Faydia	21.91	32.69	748	23.5	1967-82	16
Al-Marj	20.90	32.50	270	19	1958-91	23
Gaygab	22.02	32.72	701	22	1967-83	16
Labrag	21.99	32.79	682	13	1967-83	16
Susa	21.97	32.90	3*	0	1958-90	23
Hannia	21.52	32.84	6	0	1958-83	24
Slonta	21.72	32.59	800	38.8	1967-83	16
Bayyada	21.26	32.59	380*	23	1958-90	18

d.f.c.=distance from coast. l.o.r.=length of record.
*=estimated from contour maps.

An additional problem is that the record at some stations is incomplete, so data are sometimes missing (Appendix 2a).

Although the use of calendar years in presenting climatic data is standard international practice, this practice has the undesirable consequence of splitting winter wet seasons in climates such as those experienced in Libya. It seems therefore closer to the physical situation to start each year in the middle of the dry season, and to work with annual totals for what may be called 'climate years'. Consequently, annual totals were calculated for years beginning in July and ending in the subsequent June (Figure 5.2). This starting point is arbitrary, but less arbitrary than January.

5.2 Rainfall characteristics

5.2.1 Annual rainfall

Table 5.2 shows the mean, standard deviation, minimum and maximum precipitation over complete climate years. Figure 5.2 shows the corresponding histograms. Even omitting incomplete years, there are several problems with these data. Generally, the number of years is rather low for various stations, such as Batta (10), Al-Kouf (12) and Faydia (15). Specifically, there are some dubious sections in the data, such as the zero precipitation supposedly recorded for Shahhat in February and March 1985.

The annual rainfall data show a picture of considerable variability, in both space and time. The wettest station is Shahhat, with a mean of 568 mm, and the driest is Bayyada, with a mean of 301 mm, roughly a two-fold range over the study area. Even more important in many ways is the variability over time that emerges from examination of the standard deviation, minimum

Table 5.2 Annual precipitation for climate years in mm

station	n	mean	std.dev.	min	max	yrs below 300 mm n	yrs below 300 mm %
Shahhat	48	568.3	123.7	376.2	870.5	0	0
Bayda	32	461.9	109.0	288.1	758.2	1	3
Batta	10	411.3	125.9	196.0	678.5	1	10
Al-Kouf	12	400.6	92.5	254.1	597.8	1	8
Gobba	31	389.4	122.1	224.6	702.2	8	26
Faydia	15	386.9	135.2	218.0	685.9	2	13
Al-Marj	23	371.8	113.3	194.0	575.0	7	30
Gaygab	16	358.5	110.6	204.4	609.0	6	38
Labrag	16	351.5	133.2	149.6	590.0	6	38
Susa	22	350.5	78.4	217.3	516.0	4	18
Hannia	24	336.0	136.6	122.6	765.5	7	29
Slonta	16	304.5	90.7	176.8	474.5	8	50
Bayyada	18	301.3	95.0	134.5	514.0	9	50

and maximum. The most striking example is perhaps Hannia, with a standard deviation of 137 mm, and a range over 24 years from 123 mm to 766 mm. In general, the standard deviation is of the order of 100 mm, for both wet and dry stations, implying a substantial risk of both dry years in which crops may fail, and wet years with greater soil erosion hazard. The risk of dry years is summarised as the number of years with below 300 mm (Allan, 1981; FAO, 1969), and the corresponding percentage, varying from 0 for Shahhat to 50 for Slonta and Bayyada.

Detailed analysis of monthly and yearly data allows some important aspects of the rainfall regime to be outlined. These are seasonality, spatial distribution and temporal variability. For some stations and some years, daily rainfall data are available (Appendix 2b), which will be examined later in the chapter.

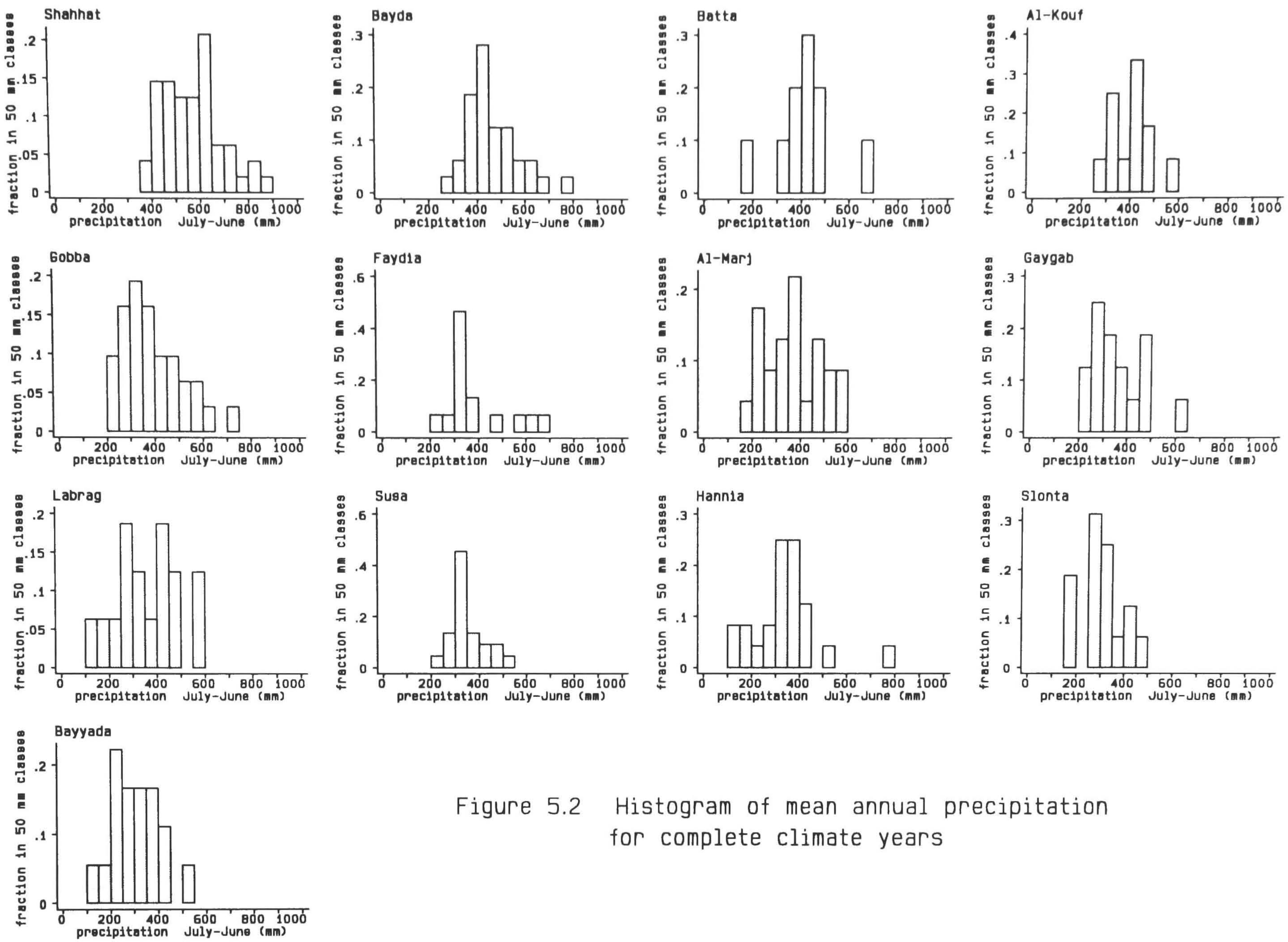


Figure 5.2 Histogram of mean annual precipitation for complete climate years

5.2.2 Rainfall seasonality

The seasonality of precipitation was studied using these 'climate years', starting in July and ending in June. The mean monthly precipitation, using only data from years that are complete, is shown in Figure 5.3. The line graphs are arranged in order from the wettest station, Shahhat, to the driest, Bayyada. The same vertical scale is used for all graphs, so that both seasonality and actual amounts may be compared. The broad similarity of seasonal pattern is evident, over the twofold range of annual totals from about 300 mm to nearer 600 mm. In most cases there is a steady rise in monthly means from July to a peak in January, and a steady fall until June. The apparent exceptions, such as Al-Kouf, may not show any real deviation, but rather reflect the irregularities present in a small sample of years.

The graphs show that there is a wet season lasting between 6 and 7 months during which more than 90 percent of the rainfall occurs. On the other hand, the dry season lasts between 5 and 6 months during which less than 10 percent of the rainfall occurs. However, even when rain falls during any of the summer months it is usually in small quantities, and coincides with high temperatures; therefore, this rain tends to evaporate quickly, sometimes before reaching the ground. On the other hand the wettest months are also the coldest months; therefore, the evapotranspiration rate is relatively low and rainfall is very effective in the study area.

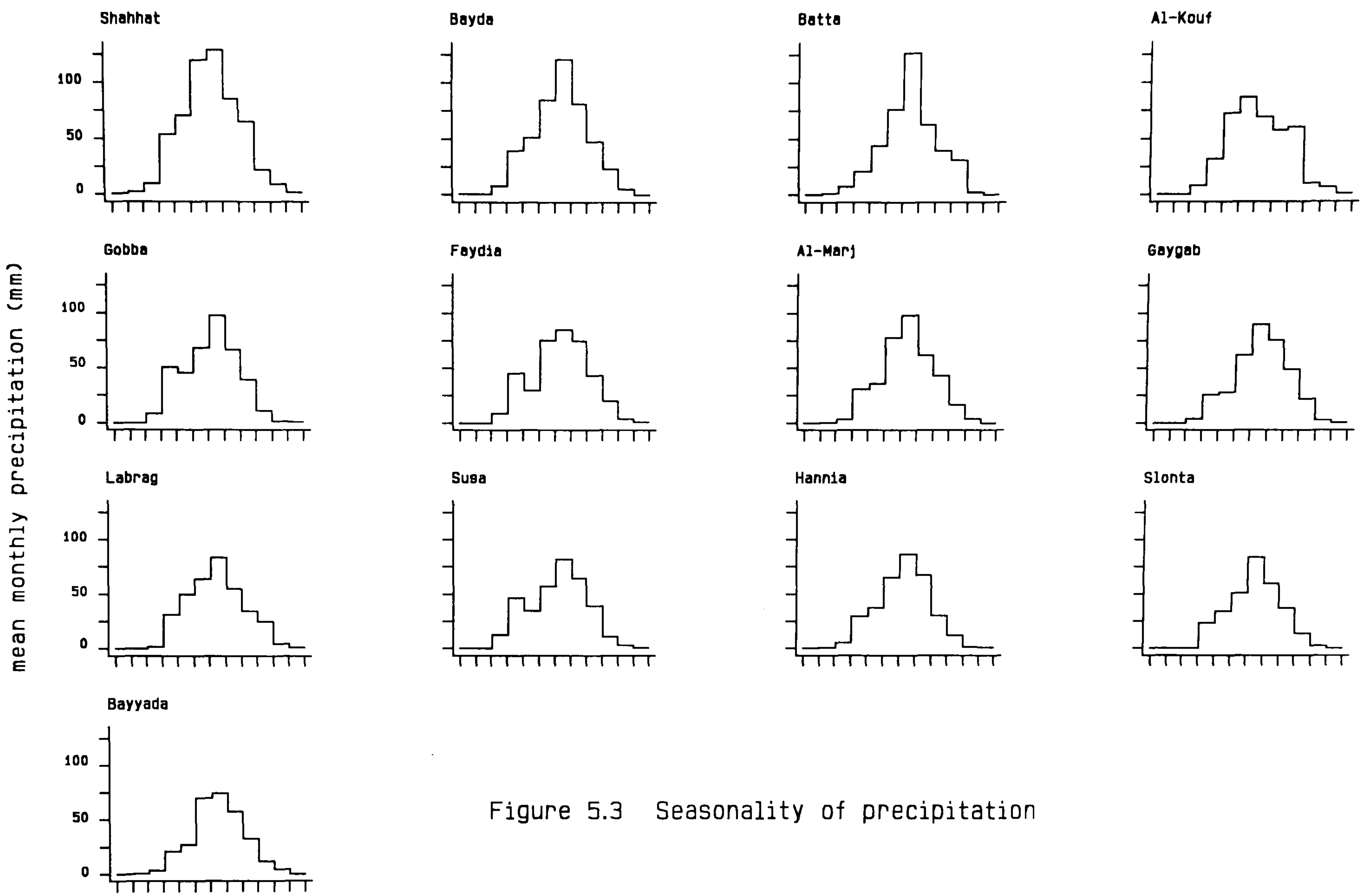


Figure 5.3 Seasonality of precipitation

The similarity of seasonal pattern is more evident when each monthly mean is shown as a proportion of the annual mean, thus showing each precipitation pattern on a relative scale, as in Figure 5.4. There is a stepped curve for each station on this graph. Al-Kouf, with a maximum in December, and a relatively low proportion of the annual total in January, is the main anomaly on this graph.

The most important feature of the precipitation regime as far as soil erosion is concerned is the relatively rapid onset of the wet season, usually in October, at a time when vegetation cover is restricted. This is shown quite well by Figures 5.3 and 5.4.

In some years the rains commence in September or early October as light showers but occasionally as violent downpours that result in rapid runoff and serious flooding in the seasonal stream beds. In addition, during this period the vegetation cover is not dense enough to protect the soil. Furthermore, surface crusts and sealing, which were recorded at most of the sites, contribute to runoff occurrence by reducing the infiltration rate. Hence this period is very critical as far as soil erosion is concerned (Table 5.3).

Table 5.3 Maximum rainfall in September and October (mm).

station	Shahhat	Bayda	Batta	Gobba	Susa	Slonta	Bayyada
Sep.	66.4	77	42	76.5	154	1.4	21
Oct.	168.4	132.2	138*	183*	172*	87.5	105*

*=figures were taken from incomplete years.

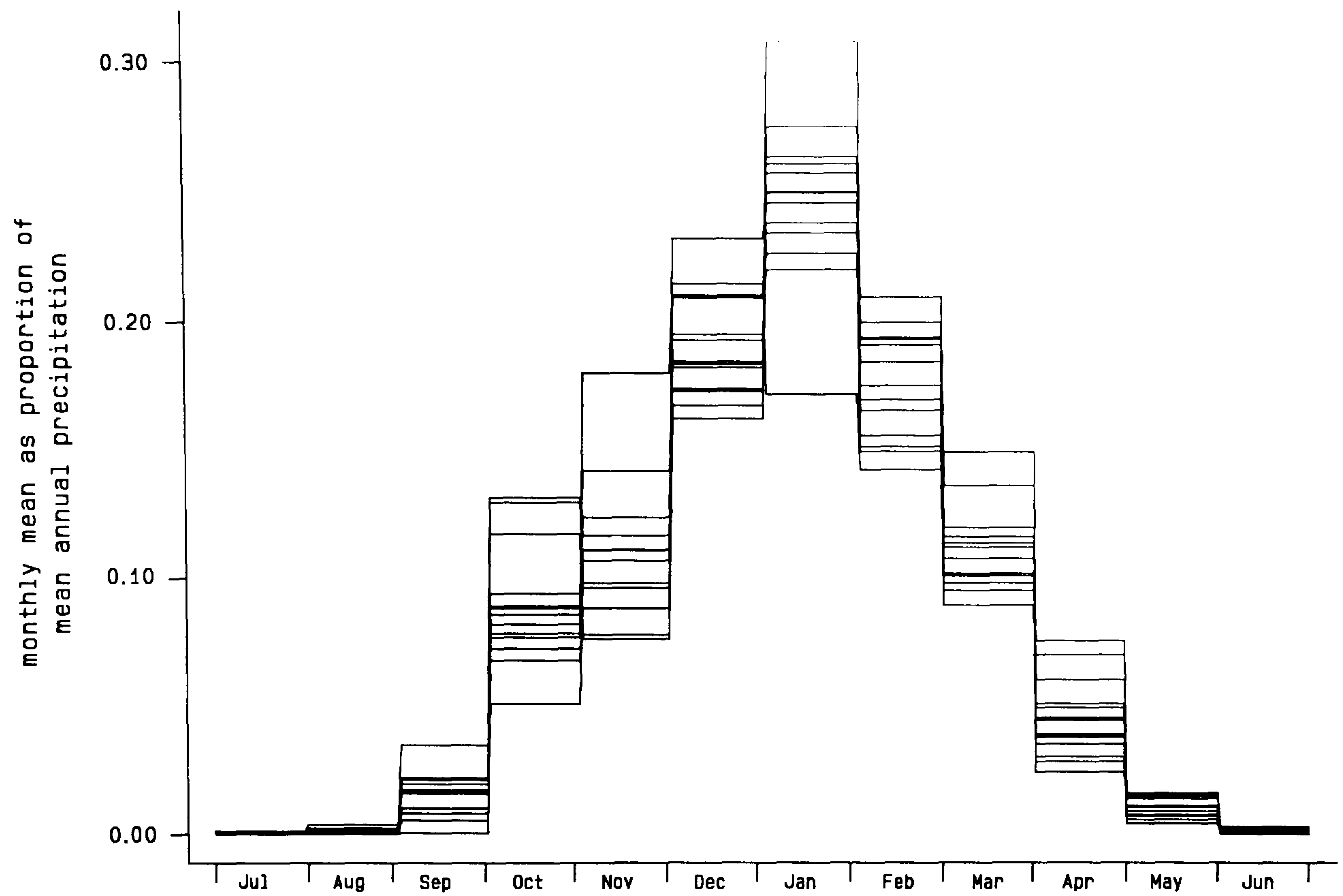


Figure 5.4 Seasonality of precipitation

From an agricultural point of view, insufficient rainfall at the beginning of the rainy season, even when the annual total might be close to normal, usually affects the grain yield production. These conditions apply also to livestock production, which is dependent on grazing.

However, it must be remembered that these data and these graphs refer to mean precipitation, and ignore the substantial variability from year to year referred to earlier. The onset of the wet season is investigated with daily data below (section 5.2.4).

5.2.3 Spatial distribution

The rainfall quantity for each station is affected by proximity to the sea, elevation and its location as related to rain-bearing winds. One example is that of Gobba and Batta stations. Although Gobba is at higher elevation than Batta, and both are the same distance from the coast, Batta receives the higher amount of rainfall. The main reason for this is that Batta is located on the western side of the Jabal Al-Akhdar, and so is more exposed to the rain-bearing winds than Gobba.

Slonta is an example of how proximity to the sea affects the amount of rainfall received. Although this station has the highest elevation its rainfall amount is the second lowest (Table 5.2). In addition to its inland location, 38.8 km from the coast, Slonta is also located right on the boundary of the steppe region, and it is near the desert. This region is a rain shadow region, and it is near the desert. This region is a rain shadow area and is characterised by semi-arid conditions. Distance from the sea is also responsible for the lower rainfall characteristics at Bayyada although it is located on the western side which is exposed to the rain-bearing winds.

In addition to the extension out of the northern slope of Al-Jabal into the Mediterranean, a combination of high elevation, proximity to the coast and being the first ground to be encountered by the moist westerly and north-westerly winds means that the area around Shahhat and Bayda on the second escarpment receives the highest amount of rainfall. However, Slonta has a higher elevation than Shahhat but receives a smaller amount of rainfall, thus indicating that the higher rainfall zone does not necessarily coincide with the higher elevation areas (Table 5.1). Also, Shahhat, which is on the central part of the northern slope, receives a higher amount of rain than Gobba in the eastern part of the second bench, Bayyada in the western part of the second bench and Susa, which is a coastal station. To summarise, the central area of the northern slope around Shahhat and Bayda is the zone of maximum rainfall totals. From this area these totals decrease rapidly in all directions.

5.2.4 Temporal variability

Marked rainfall variability over time is one of the main climatic characteristics of the area. Rainfall fluctuates considerably from one year to another, as already indicated in Table 5.2. An example of this is Shahhat. The average is 568.3 mm but in 1976-77 only 376.2 mm and in 1977-78 as much as 870.5

mm were recorded.

Apart from year to year variability, extreme variations from month to month are also found (Table 5.4). From the record, each month has been completely dry or almost dry at least once, and in every month it is possible to have a daily fall greater than the monthly mean.

The tremendous variability possible in every month at every station is shown by Figure 5.5, with curves for maximum and minimum for each month in the period of record, again only using complete climate years. It can be seen that even for stations with a mean annual precipitation of about 300 mm, there is a fair chance that individual monthly precipitation exceed 200 mm. The analysis of variability from year to year is taken further in Figure 5.6, which focuses on four selected stations: Shahhat, the wettest, and that with the best record; Gobba, with intermediate rainfall; and Slonta and Bayyada, the driest stations. The curves shown are the minimum, lower quartile (25% of years are drier), median (50%), upper quartile (75%) and maximum. For the driest months, these curves are often close or even superimposed. Whilst for the wettest months the curves show the substantial variability from year to year once again, features such as the fairly rapid onset of the wet season in October (or sometimes September) are brought out clearly. For example, the upper quartile (indicated by the second highest curve) shows the precipitation exceeded 1 year in 4, and so represents a level of risk that is not especially extreme.

Table 5.4 Monthly variability of rainfall (mm).

S.Name	Shah-hat	Bayda	Batta	Gobba	Susa	Slonta	Bayy-ada
Jul.max	10.5	7.0	0	0	0	0	0
min	0	0	0	0	0	0	0
Aug.max	42.0	16.0	10.0	0	0	0	9.0
min	0	0	0	0	0	0	0
Sep.max	66.4	77.0	42.0	76.5	154.0	1.4	17.4
min	0	0	0	0	0	0	0
Oct.max	371.0	132.2	68.7	183.0	125.5	87.5	74.5
min	0	0	0	0	0	0	0
Nov.max	198.0	176.5	79.0	129.0	118.5	87.1	104.0
min	3.0	4.0	8.0	0	1.0	0	0
Dec.max	434.8	235.2	285.4	244.5	101.5	226.5	172.0
min	8.0	2.5	7.5	3.5	0	8.0	2.5
Jan.max	332.1	252.5	219.4	324.0	202.0	243.7	156.5
min	20.8	18.3	38.0	4.8	12.0	14.0	9.3
Feb.max	284.5	300.0	140.0	293.3	180.5	171.0	281.5
min	0	15.3	0	0	13.5	9.5	5.5
Mar.max	230.1	305.0	116.0	127.6	113.3	101.0	89.0
min	0	0	0	0	0	0	8.0
Apr.max	165.7	147.1	213.7	96.0	45.9	48.0	100.5
min	0	0	0	0	0	0	0
May.max	72.1	87.0	10.0	14.0	23.0	15.1	47.5
min	0	0	0	0	0	0	0
Jun.max	31.4	0	0	26.0	12.0	5.0	0
min	0	0	0	0	0	0	0

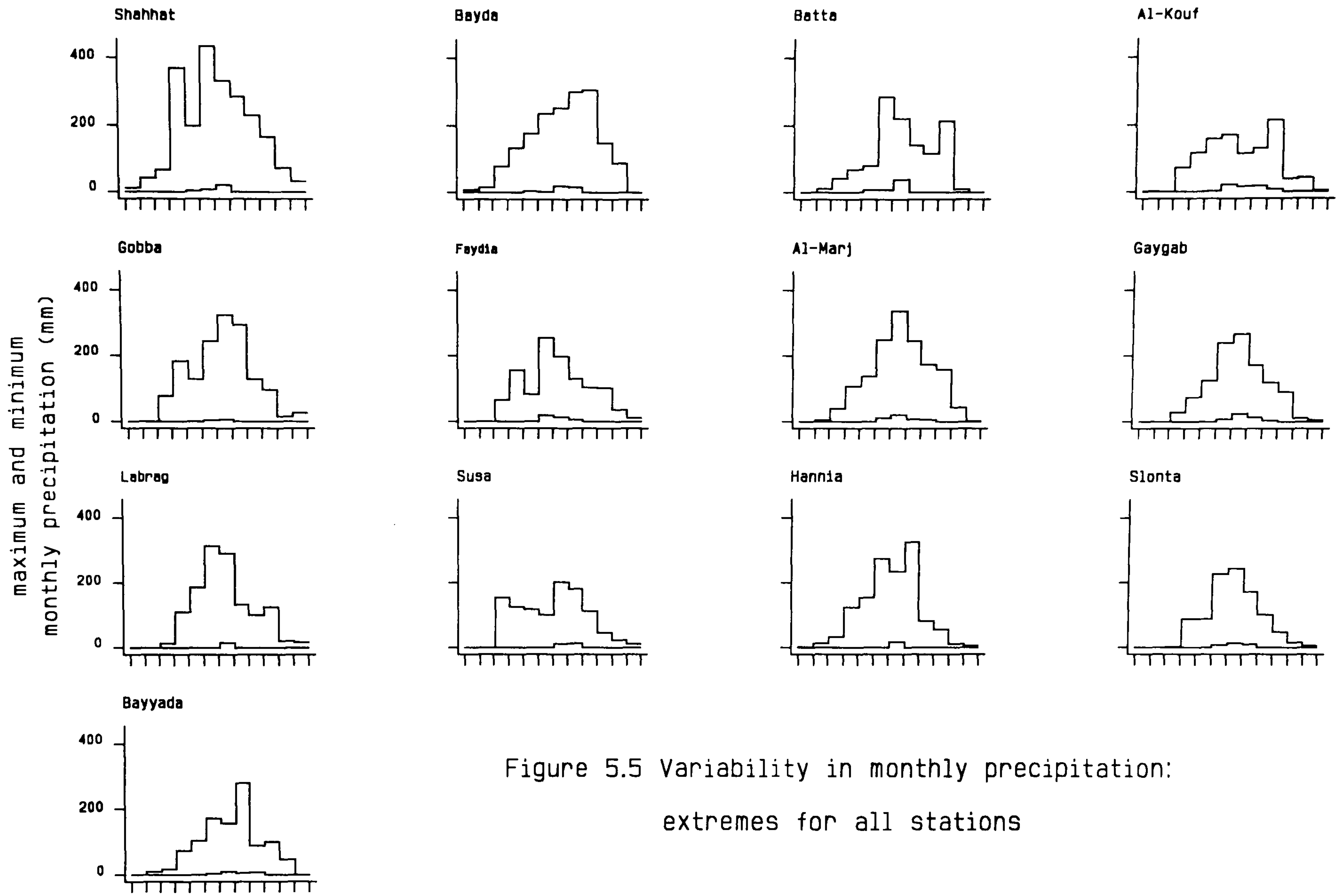


Figure 5.5 Variability in monthly precipitation:
extremes for all stations

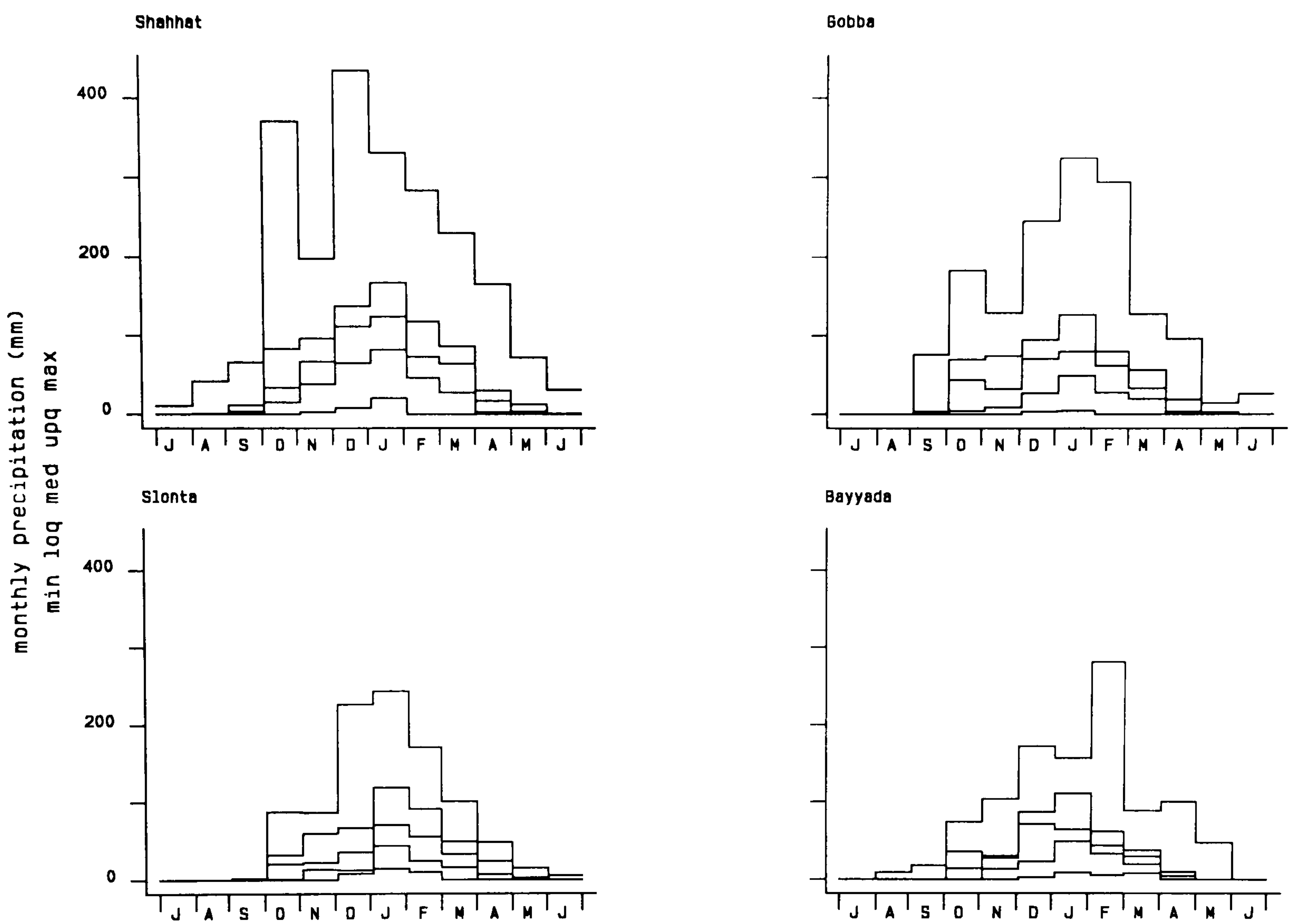


Figure 5.6 Variability in monthly precipitation:
quartiles for selected stations

Temporal variability also can be illustrated by comparing the number of raindays for some stations (Table 5.5). From this table it is clear that rainfall can be concentrated in a few days. With so few raindays soil moisture storage is limited and thus, plants will be under stress in the dry season. Furthermore, a long dry season can increase the risk of fire which is one of the causes of vegetation cover clearance. The variability and hence intensity of rain is typically greater at the start and finish of rains than in the mid-season, thus enhancing the risk of soil erosion. Even however, in the middle of the rainy season, with soil moisture usually high, the soil's ability to absorb water is lower and therefore, any amount of rain might create surface runoff and cause soil erosion.

Table 5.5 Number of rainy days for some stations.

station	length of record	number of rainy days		
		mean	min	max
Shahhat	1981-93	70	47	81
Al-Kouf	1981-82	63*	-	-
Hannia	1981-82	41*	-	-
Slonta	1981-82	32*	-	-

*=the actual number of rain days for one climatic year.

It has been reported by the FAO (1969) that the number of animals in the study area was correlated with rainfall variation. This fact is important in terms of soil erosion, especially in marginal areas, if a series of wet years is followed by a long drought. Stocks of animals are built up in the former leading to overgrazing in the latter. In addition, such areas are also liable to water erosion since flash floods still can occur in dry years (Jackson, 1989).

5.2.5 Daily rainfall

The daily rainfall was analysed for Shahhat station, where a record of 13 years of daily rainfall for 1981-93 is available. These 13 years included 4748 days. It rained on 910 days, there was a trace of rainfall on 12 days, and no rain was recorded on 3826 days. However, as mentioned earlier, according to the record no rain was observed during February and March 1985, which must be regarded as dubious. The probability of raining on any day is 910/4748, or 19.2%, which must be considered as a slight underestimate of the true figure because of the doubt about these two months. Some characteristics of the daily rainfall may be pointed out. These are:

1. The total number of raindays varied between 81 days in 1991-92 and 47 days in 1984-85. Most of these raindays occur in the months of November to February. During these four months it does not rain every day, but dry spells occur within each month. For example, in December 1981 a total of 41.2 mm was received in 5 days, half of it in one day, and in January 1982, the monthly total of 52.9 mm fell in four days and the rest of the month was dry. In 1991-92, some relatively heavy showers occurred. As much as 86.5 mm fell in one day, 158.9 mm fell in one 8 day period and 435.1 mm were recorded in December while the annual total was 807.7 mm. Furthermore, the number of raindays for any of these wet months can be less than that for some dry months. For example the number of raindays in January in 1987 was 9, while it was 16 for March and 10 for April of the same year.

Daily rain can be used to determine the beginning and end of the rainy season. The length of the rainy season is important in determining the extent of the growing season. However, the wet season sometimes starts with a short spell of wet weather followed by a long dry spell, giving what Sumner (1988) called a false start to the rainy season. In Shahhat in 1992, the first rain of the season was on 5 September followed by 78 dry days before the next rain was received.

2. The months from November to February receive a mean of about 8.5 mm per rainday. However, the variability about this mean can be very great. In November 1993 and also in December 1989, the mean was only 2.9 mm. In December 1991 it was as much as 19.8 mm.

3. The mean value is unstable, and can be pulled up by a single day, as in December 1991, when 86.5 mm fell in one day. In addition, a large proportion of the raindays occurs singly (28.6%)), or in groups of two days (21.3%). Spells longer than two days are less frequent but can occur in any month.

The data are best investigated in terms of complete climate years, as explained earlier. There are twelve such years, from 1981-82 to 1992-93. Plotting rainfall against days after July 1, Figure 5.7a shows both the seasonality and the irregularity, with some rainfalls over 60 mm. The highest is 86.5 mm, observed twice.

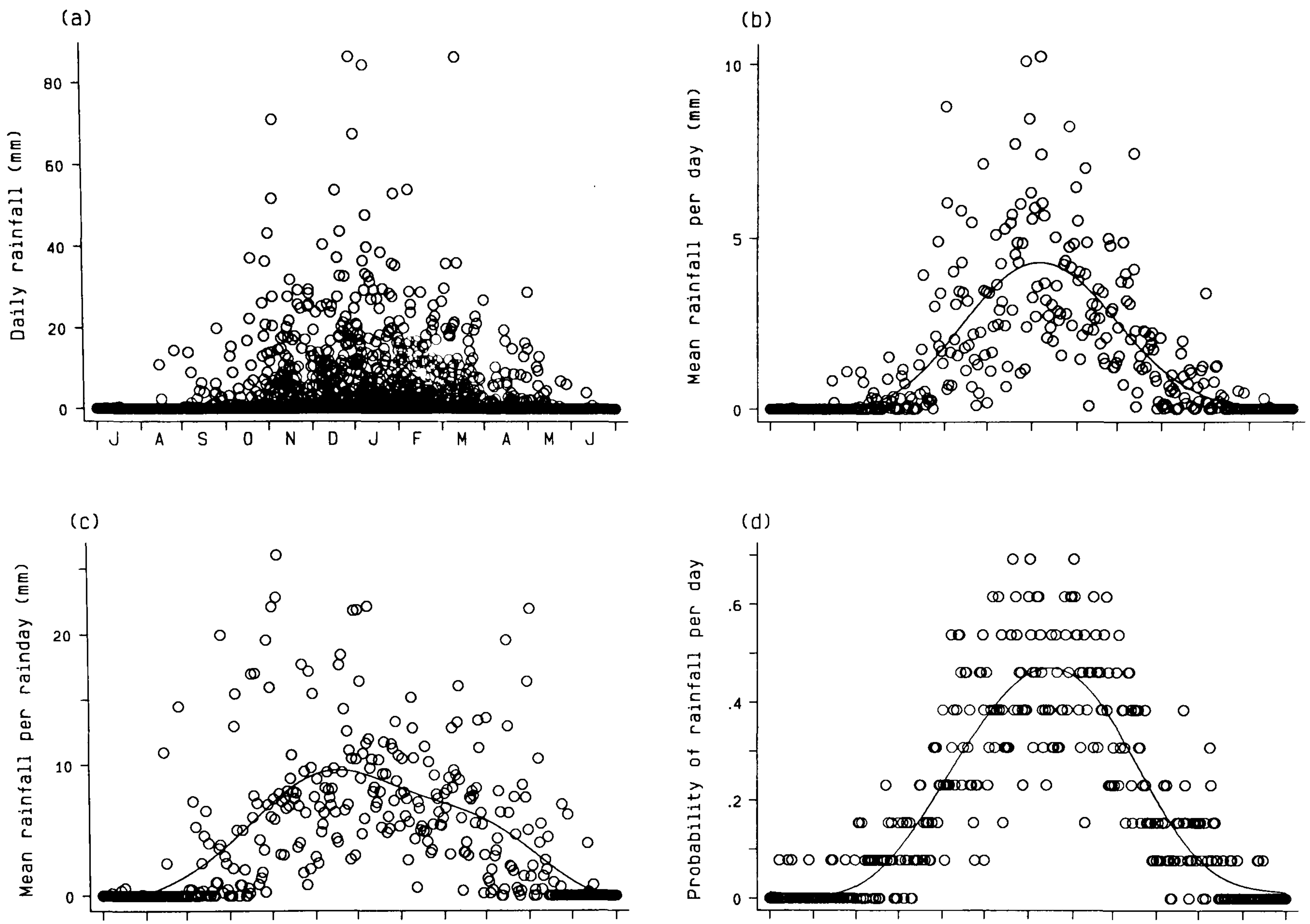


Figure 5.7 Shahhat daily precipitation 1981-93 (mm)

More order can be seen if mean rainfall per day is calculated, as shown in Figure 5.7b. These means are summarised by a smooth curve calculated as the predicted mean from multiple regression on the first three sine and cosine terms of a Fourier series in the number of days after July 1. This smooth curve is guaranteed to be periodic, so that it wraps around from year end to year start just as years do in nature. It is in this case approximately symmetric with a smooth increase and then a smooth decrease in mean rainfall per day throughout the wet season. Mean rainfall per day can be thought of the result of multiplying (mean rainfall per rainday) by (probability of rain on a given day) and these factors are shown in Figures 5.7c and d. Smooth curves were produced by the same method. Both take on a maximum in the middle of the wet season, although it is interesting and important that mean rainfall per rainday rises rather steeply in the first part of the wet season. The horizontal banding in Figure 5.7d arises from the discreteness of the data: that is, in 13 years it has rained any number of times from 0 to 13 out of 13 years. In fact, the maximum is 9.

The daily rainfalls for Shahhat are shown against time for the 12 complete climate years in Figure 5.8. This shows the detailed irregularity of the rainfalls in another way. Special attention should be given to the sudden onset of the wet season in some years, when the vegetation cover is likely to be low.

The daily rainfall data for Shahhat can be divided into wet spells in which rain fell on every day, separated by dry spells,

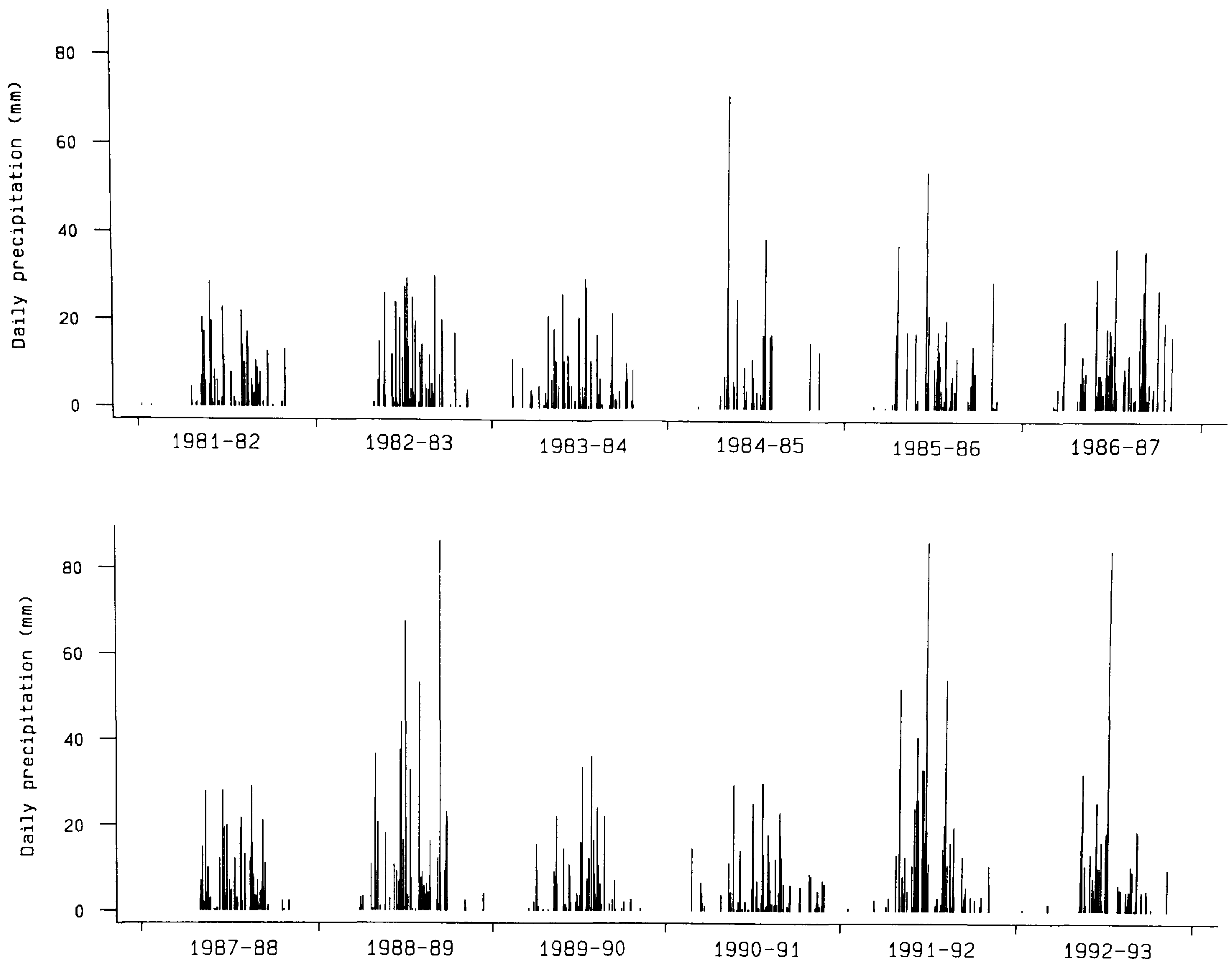


Figure 5.8 Shahhat daily precipitation 1981-93 (mm)

with no rain. Table 5.6 lists spells ending before the end of October. It can be seen that in some years there were substantial spells before the end of October, as in 1983, 1985, 1986, 1988, 1989 and 1993, with individual spell totals up to about 90 mm. In others there was little or no rain before the end of October, as in 1981, 1982, 1987 and 1992, with cumulative rainfall totals below 10 mm. Furthermore, in about one year in four, the wet season starts abruptly with a spell of over 10 mm (13.5 mm in 1983, 14.5 mm in 1990 and 14.0 mm in 1993).

The frequency distribution of daily rainfalls at Shahhat (Figure 5.9) shows a very skewed distribution. Most raindays have less than 5 mm, but rainfalls more than 20 mm also occur quite frequently, with an observed maximum in 13 years of 86.5 mm.

Daily data are also available for only two calendar years, 1981 and 1982, for Al-Kouf, Labrag, Hannia and Slonta. The pattern of rainfalls in time (Figure 5.10) shows that essentially the same characteristics of daily rainfall, such as concentration in spells or erratic or abrupt starts to the wet season, are observed as at Shahhat. The frequency distribution for these other stations (Figure 5.11) indicates a similar skewness of rainfall values, and the possibility for all stations of daily rainfalls up to about 50 mm. However, the frequency distribution for Slonta shows fewer rainfalls less than 5 mm, which may be because the observer failed to record very light rainfalls.

Table 5.6 Shahhat rainfall spells ending before end of October 1981-93.

Year	Spell end (Jul. 1 = 1)	Spell rain (mm)	Spell length (days)	Average rain (mm/day)
1981	8	0.2	1	0.2
81	29	0.1	1	0.1
81	113	6.2	3	2.1
81	120	0.5	1	0.5
1982	118	1.0	1	1.0
82	120	1.0	1	1.0
1983	46	13.5	2	6.8
83	67	9.0	1	9.0
83	82	1.0	1	1.0
83	84	4.0	1	4.0
83	87	3.0	1	3.0
83	101	6.0	2	3.0
83	111	0.5	1	0.5
83	114	3.2	1	3.2
83	121	37.1	4	9.3
1984	64	0.4	1	0.4
84	109	3.4	2	1.7
84	118	7.3	1	7.3
1985	62	0.5	1	0.5
85	86	0.1	1	0.1
85	99	1.0	1	1.0
85	110	90.7	7	13.0
1986	65	1.1	2	0.6
86	69	0.3	1	0.3
86	73	4.6	1	4.6
86	85	30.0	3	10.0
86	113	2.0	1	2.0
86	119	6.0	1	6.0
86	122	12.0	1	12.0
1988	86	0.4	1	0.4
88	89	3.5	2	1.8
88	93	3.2	1	3.2
88	109	10.8	1	10.8
88	114	0.4	1	0.4
88	120	89.9	4	22.5
1989	78	0.4	1	0.4
89	88	2.0	1	2.0
89	96	38.5	4	9.6
89	99	1.4	2	0.7
89	108	0.1	1	0.1
89	119	0.2	1	0.2
1990	55	14.5	1	14.5
90	74	6.5	1	6.5
90	76	4.0	1	4.0
90	81	1.0	1	1.0
90	115	3.5	1	3.5
1991	17	0.6	1	0.6
91	72	2.9	2	1.5
91	96	1.0	1	1.0
91	101	3.0	1	3.0
91	117	13.3	2	6.7
1992	14	0.4	1	0.4
92	67	1.5	1	1.5
1993	65	14.0	1	14.0
1993	84	1.3	1	1.3
1993	122	48.9	2	24.5

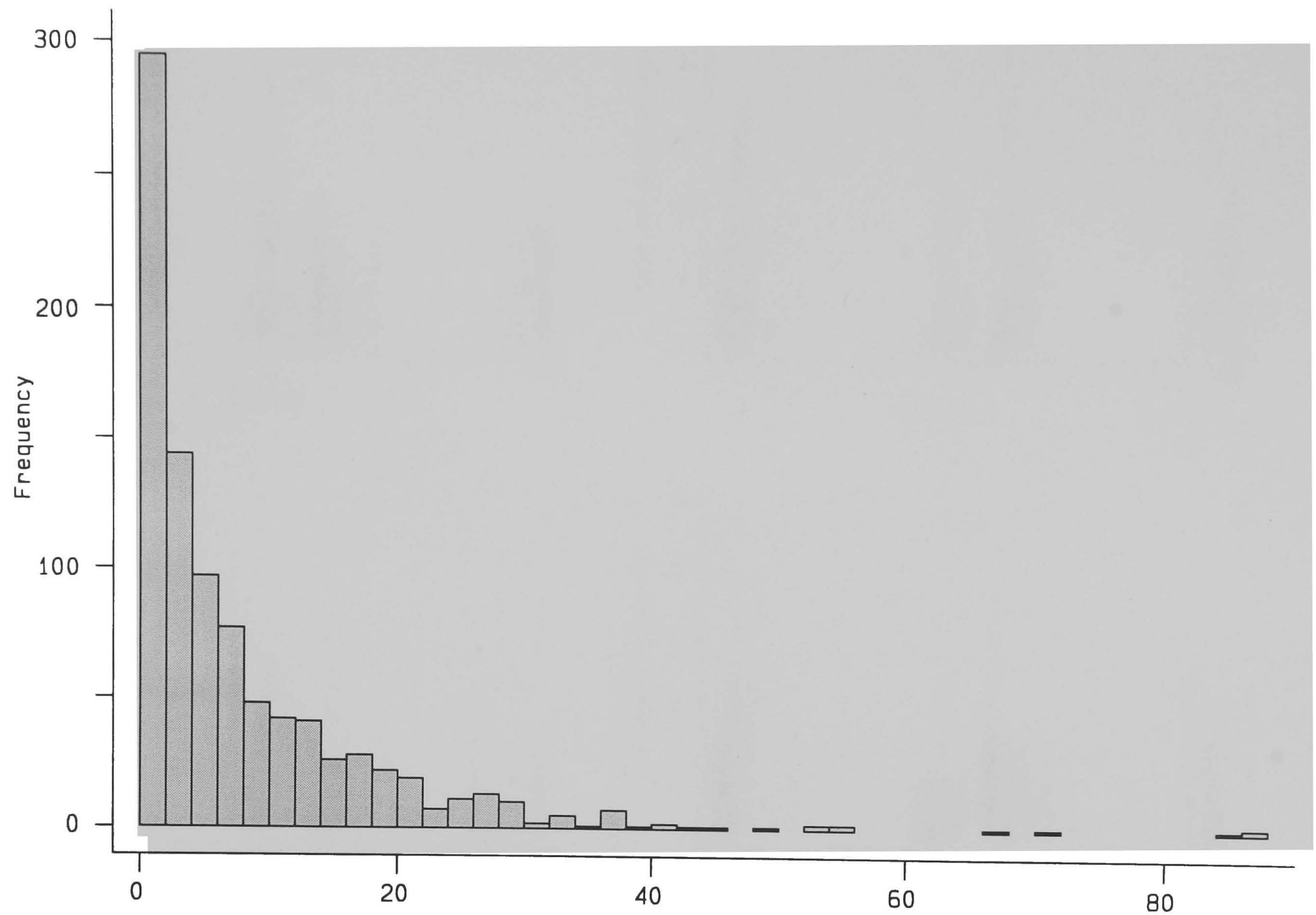


Figure 5.9 Histogram of daily precipitation for Shahhat 1981-93 (mm)

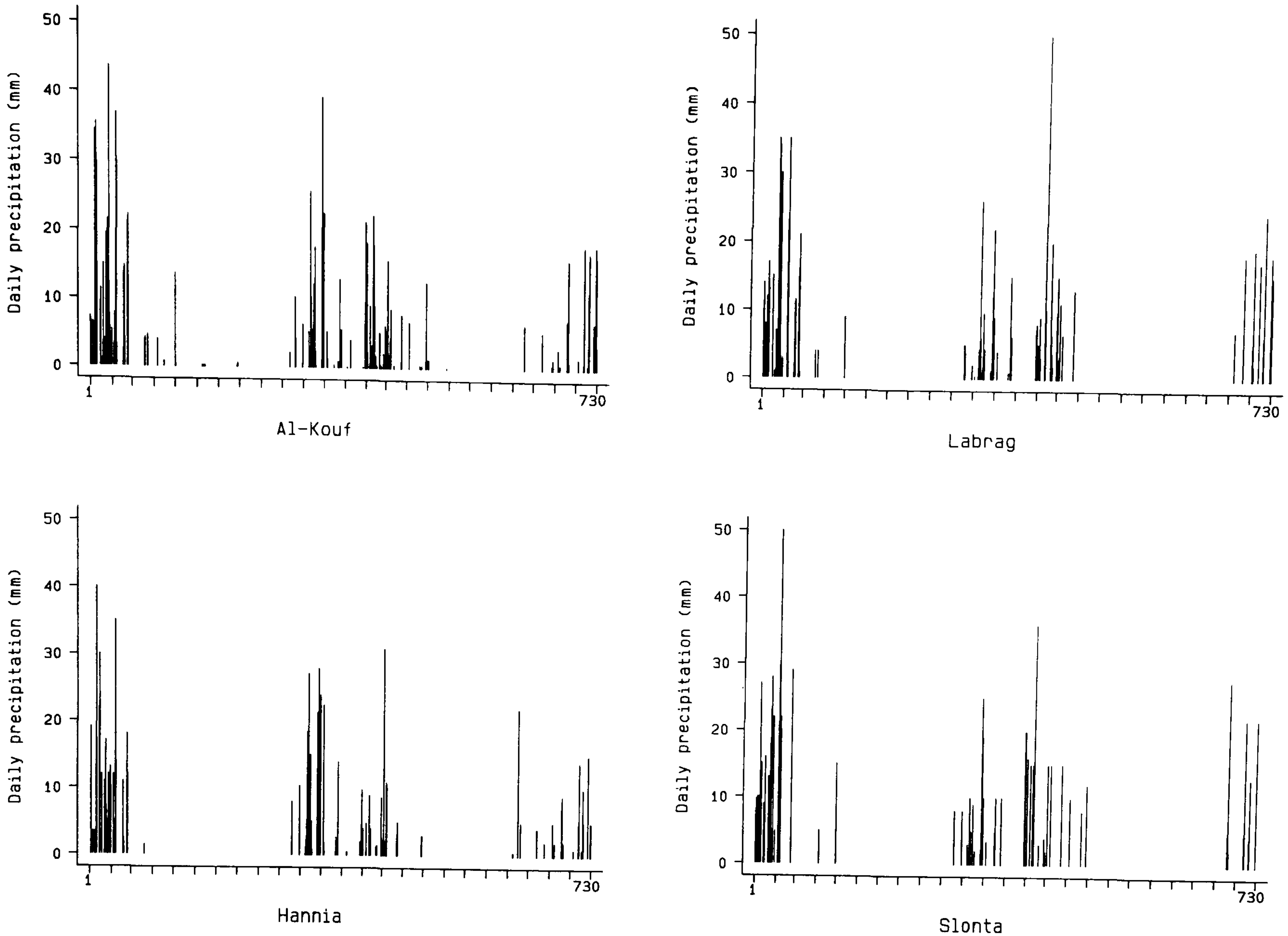


Figure 5.10 Daily precipitation for four stations 1981-82 (mm)

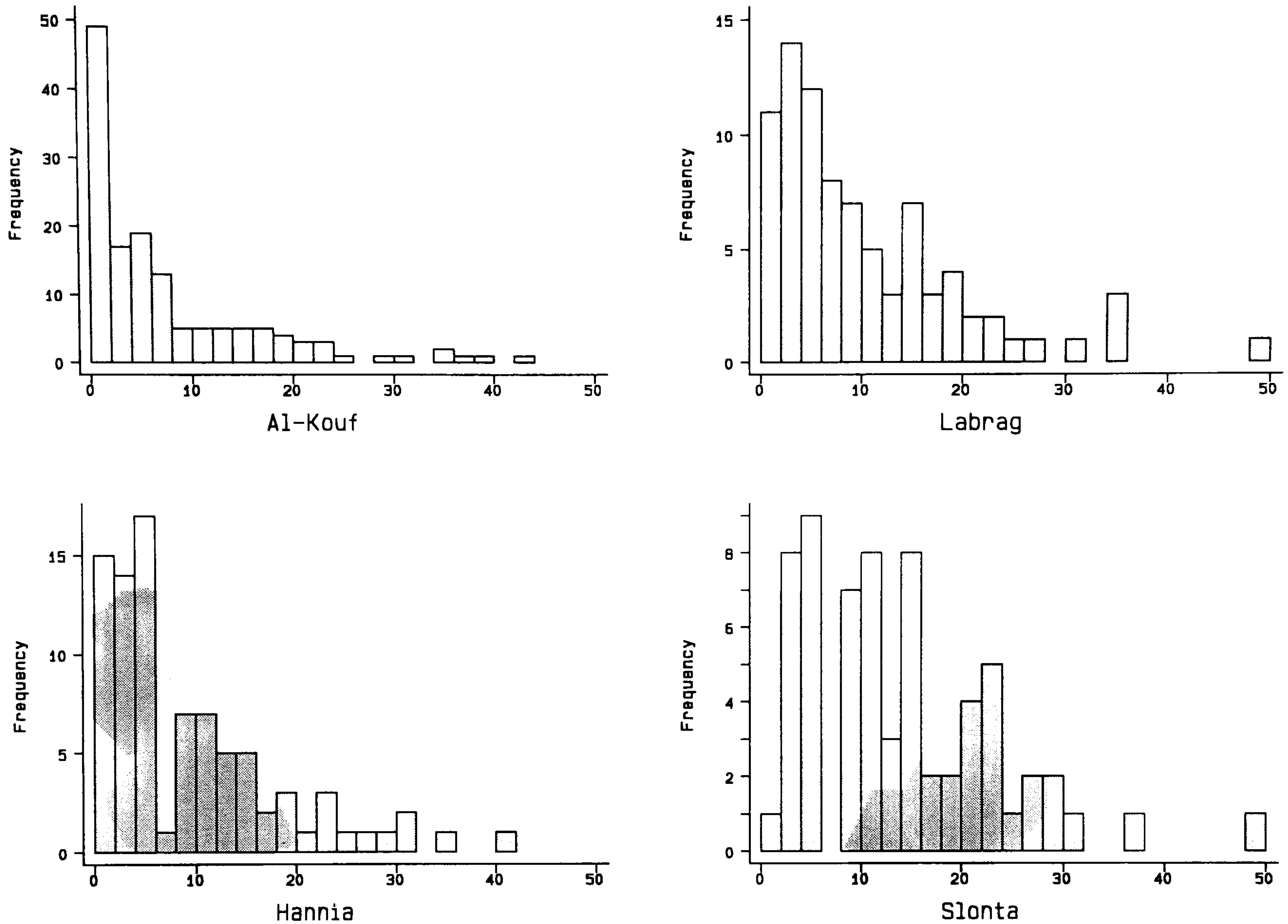


Figure 5.11 Histograms of daily precipitation for four stations 1981.82

The daily data for all these stations are summarised in Table 5.7. The two years for which data are available for Al-Kouf, Labrag, Hannia and Slonta were relatively wet for those stations, as can be seen by comparing the average annual precipitation for those two years with the average for the period of record given above. The 13 years for which data are available for Shahhat were by contrast rather drier than the period of record as a whole (average 547 mm as compared with 568 mm). The number of raindays tends to decline with average annual precipitation, as would be expected. Of equal or greater importance, however, as mean annual precipitation approaches 300 mm, are two facts: first, individual raindays may still exceed 40 mm; second, the mean precipitation per rainday may be about or above 10 mm (13.5 mm in particular for Slonta). This mean is higher at Labrag, Hannia and Slonta than at Shahhat. Thus erosion risk does not necessarily decline with mean annual precipitation.

Table 5.7 Summary of the daily data for all the stations

station	years	raindays total no.	raindays av.ann.p. /year no.	daily precipitation min mm	max mm	mean mm	sd mm	in period mm
Shahhat	1981-93	910	70	0.1	86.5	7.8	10.3	547.4
Al-Kouf	1981-82	141	70.5	0.1	43.6	7.5	9.1	532.1
Labrag	1981-82	85	42.5	0.4	50	10.0	9.5	426.8
Hannia	1981-82	87	43.5	0.5	40	9.2	8.8	399.8
Slonta	1981-82	65	32.5	1	50	13.5	9.5	437.2

5.3 Conclusion

The data show that there is a considerable variability of rainfall in the study area. In addition to the possibility of crop failure as a result of dry years, soil erosion risk increases during wet years. Furthermore, the rapid onset of the rainy season during September or October while the soils are bare or poorly protected by vegetation usually increases the chance for runoff generation; hence the risk of flooding and very serious soil erosion will be increased as well.

In general, rainfall is moderate, and mostly occurs as single showers of short duration, which are occasionally relatively heavy. Such amounts of rain, usually characterized by high intensity, can produce minor runoff on areas of deep soils and a dense cover of vegetation or a larger runoff on areas having shallow stony soils and scanty vegetation. However, in the study area deep soils are limited to some parts of the central north slope and the rest of the area is covered with shallow soils characterized by poor storage capacity.

It is also clear that the rainy season can be concentrated in a few rainy days while the rest of the year is dry. On the one hand during a long dry season plants will be affected as a result of lack of moisture. On the other hand, the destruction of vegetation cover through overgrazing or by fire will be increased. The result is reduction of vegetation cover and thus more soil erosion.

Chapter 6

Factors influencing soil erosion by water in the study area

6.1 Introduction

Soil erosion by water is a function of a number of interacting factors including soil properties (e.g. texture, depth, organic matter content, infiltration rate); vegetation cover and land use; slope angle, length and position. In order to compare the interrelationships of these various properties as they influence the degree and intensity of erosion, a cross tabulation analysis was conducted for all properties measured at each of the six sites.

From field observations supported by laboratory results, three sites, Lussaita, Bayyada and Batta, appear to be very similar. The similarity appears to be due to the fact that they have the same distribution of land use according to slope position, i.e. the upper slopes of these sites have natural vegetation cover and their lower slopes are cultivated (Plate 6.1). Furthermore, these slopes are valley side slopes, a fact assumed to be important in erosional and sedimentational processes along the slopes. In order to simplify discussion and reduce repetition, these sites will be treated together.

At the Magra site, however, the above situation is almost reversed. Because of the topography of this site, most of its upper slopes are more accessible than lower slopes. Therefore, the upper slopes are cultivated and the lower slopes have the natural vegetation. This situation affected the soil properties and hence the distribution of erosion features; thus the Magra site was dealt with as a separate case.

Plate 6.1 Usually middle and lower slopes are cleared of their vegetation cover for cultivation, and upper slopes are left for natural vegetation. Vines on lower slope in foreground.

Gobba and Shahhat, the two remaining sites, differ from the remainder in having a more complex soil pattern, each with two different soil types, namely vertic brown and ferric red soils. The former is the soil type of 9 slopes in Gobba and 3 slopes in Shahhat and the latter is the soil type of 1 slope in Gobba and 7 slopes in Shahhat. Both sites are also similar in that no natural vegetation was encountered on any of the surveyed slopes. However, as Gobba slopes are closed depression slopes, whilst those at Shahhat are valley-side slopes, and at Gobba some agricultural areas are irrigated, it was considered that these sites were sufficiently different to warrant separate consideration.

Assessment of intensity of soil erosion is based on type and number of erosion features recorded on each slope position. Therefore, the slope that recorded the highest frequency of gullies, concentrated flow and rills is classified as the most eroded slope at the site.

6.2 Lussaita, Bayyada and Batta sites

6.2.1 Topographic relationships

The relationship between slope angle, slope length and soil erosion is well documented in the literature on soil erosion by water (e.g. Bryan, 1979; Bryan and Poesen, 1989; Gerrard, 1992; Morgan, 1980 and Quansah, 1985). However, slope angle can influence soil stability in two ways: first, an increase in slope angle decreases the resistance of soil particles to detachment, because of gravitational forces, and second, it increases the erosivity of running water because of increased water flow velocity. On the other hand, length of slope is important because the total discharge increases with slope length. Therefore, as slope length increases the incidence and severity of erosion are also assumed to increase.

At Lussaita, slope angles range between 4.3° and 9.3° and slope lengths between 238 and 547 metres (Table 6.1). Soil erosional features such as rills, gullies and concentrated flow were recorded on 7 of the 10 slopes studied, on slope angles ranging from 4.9° to 9.3°. Interestingly the distribution of erosion features did not follow the expected link between increased slope angle and slope length, as the most eroded slope was the shortest (283 m) with a 4.9° slope (Figure 6.1).

Table 6.1
Summary of results, showing relationships between number of soil erosion features and slope length and angle.

area	slope no.	L metres	ST degrees	number of gul.	ril.	cfl
Lussaita	1	314	9.3	0	0	1
	2	547	7.7	0	0	2
	3	382	6.2	0	0	0
	4	337	4.3	0	0	0
	5	253	7.8	1	0	0
	6	367	8.1	0	0	1
	7	238	4.9	1	1	1
	8	290	6.9	0	0	1
	9	289	5.0	1	0	0
	10	308	7.8	0	0	0
Bayyada	1	412	5.4	0	1	1
	2	410	3.9	0	1	1
	3	399	3.1	0	1	1
	4	410	2.1	0	0	0
	5	314	4.0	0	0	0
	6	453	6.1	1	0	0
	7	353	6.5	1	1	1
	8	434	2.5	0	0	0
	9	624	2.3	0	1	0
	10	308	2.5	0	0	0
Batta	1	226	10.2	1	1	1
	2	264	6.7	0	1	1
	3	274	8.0	1	0	1
	4	294	5.4	0	1	1
	5	237	5.9	1	0	0
	6	231	5.5	0	0	1
	7	475	7.1	1	0	1
	8	366	5.3	0	0	1
	9	254	8.6	0	0	0
	10	268	8.3	0	0	0

L=slope length ST=slope steepness gul.=gullies
ril.=rills cfl=concentrated flow

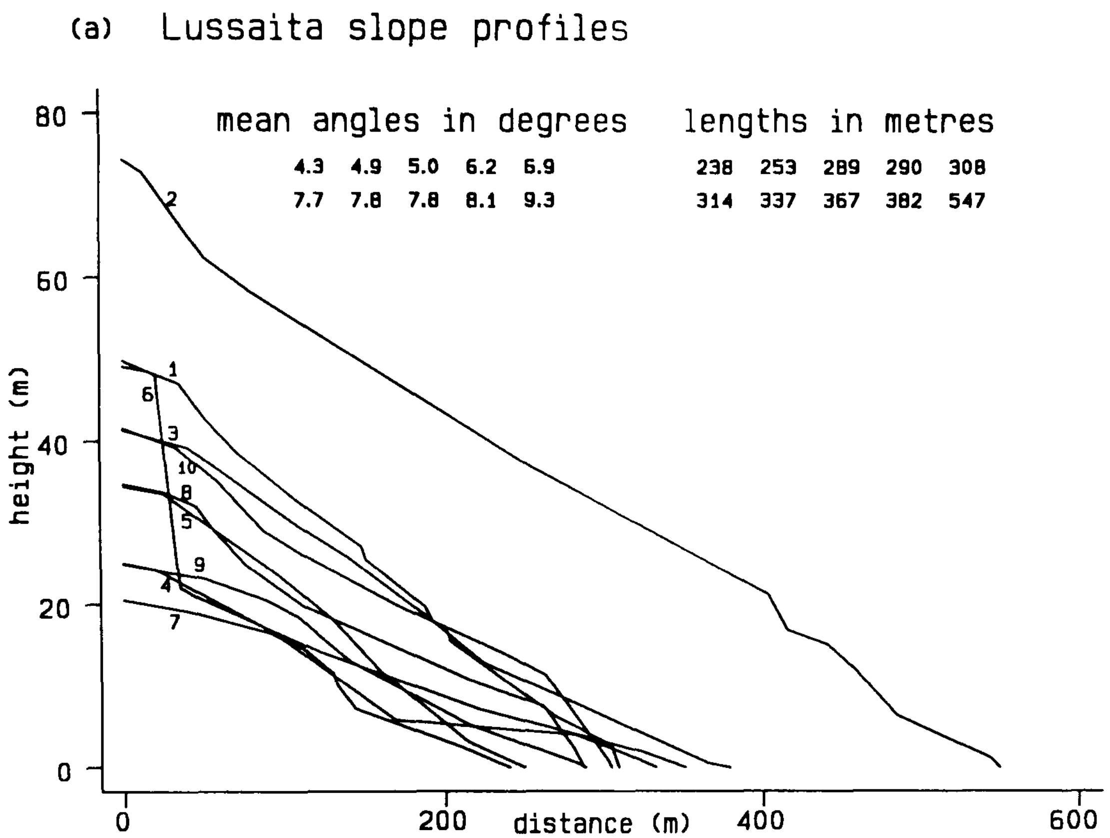
At Bayyada, slope angles vary from 2.2° to 6.5° and lengths from 308 to 624 metres (Table 6.1). Soil erosional features were recorded on 6 slopes, with angles ranging from 2.3° to 6.5°.

Here, the two steepest slopes, slopes 6 and 7, are the most eroded (Figure 6.2).

At Batta, the angles range between 5.3° and 10.2° and slope lengths between 226 and 475 metres (Table 6.1). Soil erosional features were recorded on 6 slopes, and on slope angles ranging from 5.3° to 10.2°. Of these affected slopes, the steepest and the shortest, slope 1, and the longest, slope 7, are the most eroded slopes (Figure 6.3). Unlike Lussaita, at Bayyada and Batta sites the incidence of soil erosion features and angle and length of slope shows a strong relationship.

6.2.2 The relationship between soil properties and slope position

Soil properties such as texture, organic matter content and soil depth partly reflect the influence of hillslope erosional and sedimentational activity, which involve the removal of small soil particles and organic matter from upper slopes and their accumulation on lower parts. Thus, these properties may be evaluated and their variations related to landscape position. Therefore, soil texture should become finer in the direction from the upper slope, where erosional activity is greatest, to the lower slope, where sedimentary processes are active (Kleiss, 1970; Malo et al., 1974 and Walker et al., 1968). Thus it was expected that fine texture would dominate the sites of the lower parts of the slopes. Furthermore, landscape position plays an important role in the spatial distribution of erosion features. Therefore, studying the influence of slope position on soil properties can lead to a better understanding of the relationship



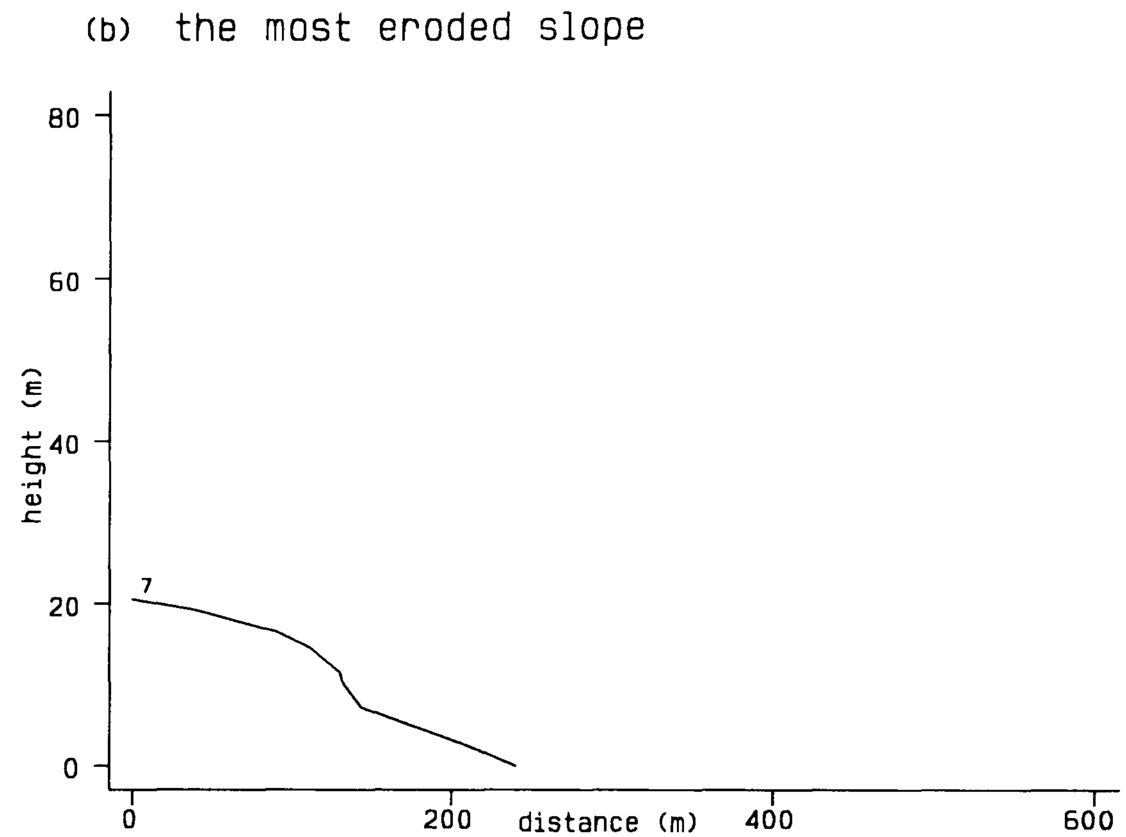


Figure 6.1 (a) shows the variations of slope angles and lengths in this site and (b) the slopes that recorded the highest concentration of erosion features

(a) Bayyada slope profiles

(b) The most eroded slopes

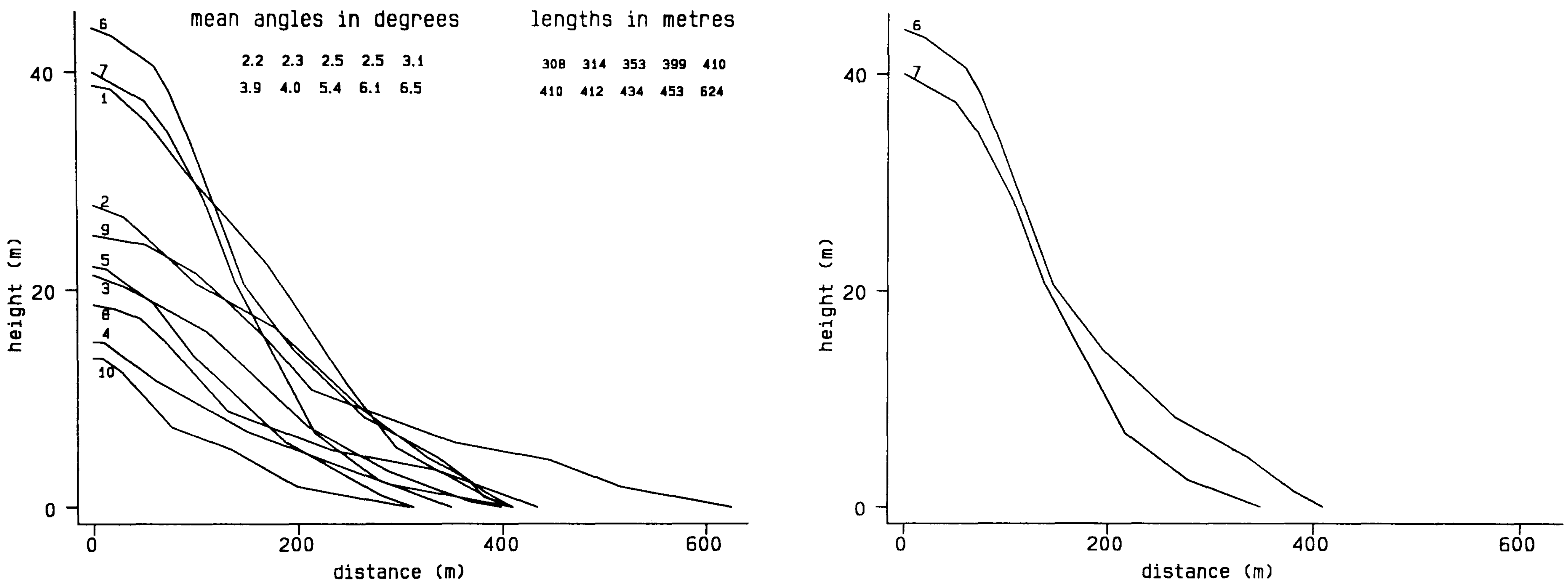


Figure 6.2

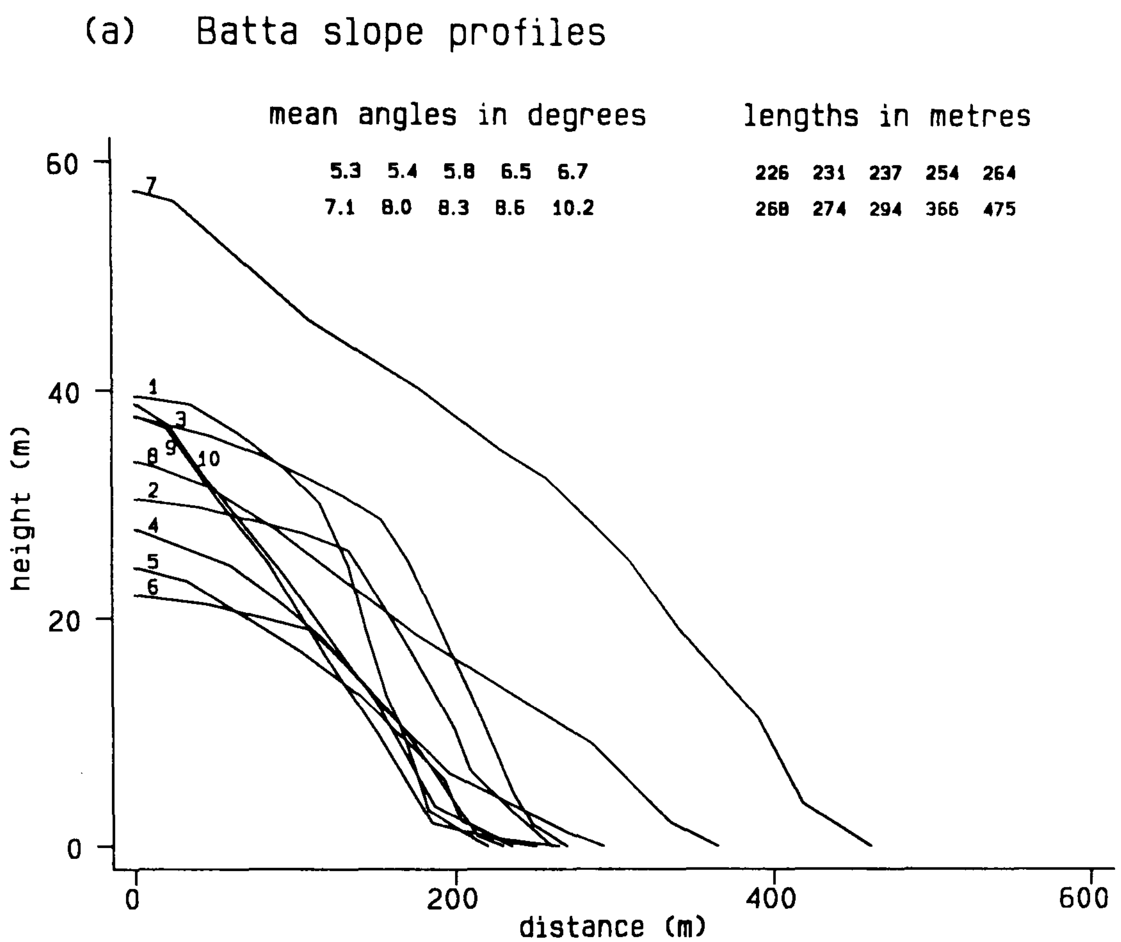
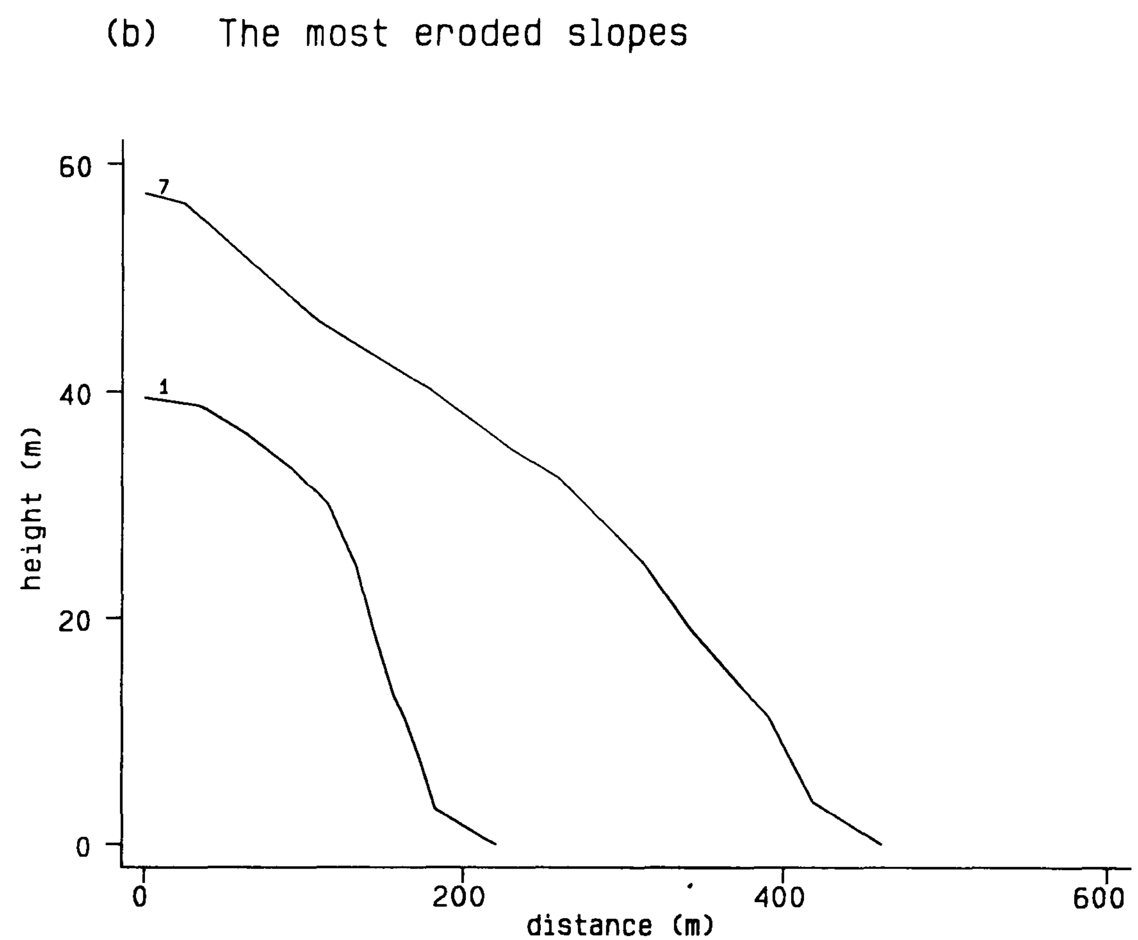

(a) Batta slope profiles
mean angles in degrees
5.3 5.4 5.8 6.5 6.7
7.1 8.0 8.3 8.6 10.2
lengths in metres
226 231 237 254 264
268 274 294 366 475
height (m)
distance (m)
1 2 3 4 5 6 7 8 9 10
0 20 40 60
0 200 400 600

(b) The most eroded slopes
height (m)
distance (m)
7
1
0 20 40 60
0 200 400 600

Figure 6.3

between soil properties and the distribution and intensity of soil erosion features (Table 6.2).

Table 6.2 Summary of results, showing relationships between frequencies and means of soil properties and slope position.

(a) Lussaita site.

slope posit.	c	tc	cl	tcl	tl	l	scl	sl	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc %
lower	6	0	2	2	0	0	0	0	33.6	1.9	6.3	4.8	28.0
middle	4	2	2	1	1	0	0	0	28.1	1.9	6.6	5.4	31.1
upper	2	1	0	3	3	1	0	0	23.2	3.1	7.3	7.3	43.1
t/mean	12	3	4	6	4	1	0	0	28.3	2.3	6.6	5.8	34.1

(b) Bayyada site.

slope posit.	c	tc	cl	tcl	tl	l	scl	sl	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc %
lower	0	0	0	8	2	0	0	0	36.9	1.7	1.9	1.8	16.7
middle	0	0	1	4	2	3	0	0	36.3	1.8	3.6	2.6	19.5
upper	0	0	4	0	1	3	2	0	26.3	2.9	3.8	6.8	27.1
t/mean	0	0	5	12	5	6	2	0	33.2	2.1	3.1	3.7	21.1

(c) Batta site.

slope posit.	c	tc	cl	tcl	tl	l	scl	sl	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc %
lower	0	0	2	8	0	0	0	0	35.1	4.0	7.1	3.9	45.8
middle	0	0	4	5	0	0	0	1	30.6	3.7	7.2	8.0	46.9
upper	0	0	3	4	1	2	0	0	31.8	4.2	9.3	9.2	55.3
t/mean	0	0	9	17	1	2	0	1	32.5	4.0	7.7	7.0	49.3

c=clay tc=silty clay cl=clay loam tcl=silty clay loam
l=loam tl=silty loam sl=sandy loam scl=sandy clay loam
OM=organic matter SD=soil depth IR=infiltration rate
pcc=per cent of vegetation cover

6.2.2.1 Soil texture

The previous hypothesis is generally confirmed by the slopes of the three sites. Most of the 16 samples with textures finer than clay loam, recorded in Lussaita, were found on lower slopes, whilst most of the recorded 10 coarse textures of silty clay loam and silty loam were on upper slope positions (Table 6.2a).

The finest textures at the Bayyada and Batta sites were clay loam and silty clay loam, recorded 17 times in Bayyada and 26 times at Batta (Tables 6.2b and c). At both sites the majority of these fine textures were found on lower slopes. The coarsest textures in Bayyada were loam and sandy clay loam, and loam and sandy loam at Batta. In general, these coarse textures were found on upper slopes of both sites.

The relationship between soil particle distribution and slope position in Bayyada and Batta however, was not as clear as at Lussaita. Bayyada and Batta upper slopes recorded more clay loam textures than lower positions, which were mainly dominated by silty clay loam texture. However, the few cases of upper slopes containing higher proportions of fine material than the lower slopes can be explained by what Wambeke (1992) suggested, namely that fine material may form stronger aggregates than coarse material and may be trapped into granules that resist disruption and are less mobile than the individual grains.

6.2.2.2 Soil depth

The erosion of material from the upper slope and deposition on the lower slope often increases soil thickness in the depressions of the lower part of the slope. Thus the steeper parts of the slope are usually associated with increased rates of runoff and erosion and decreased vertical percolation of water resulting in thin and weakly developed soils. Also, when soil depth increases in the downslope direction, infiltration rate could be expected to increase; therefore, runoff will be reduced (Donald et al., 1993 and Kachanoski et al., 1985). In fact, as will be explained later, the reverse is the case, with infiltration rates being lowest on the deeper soils of lower slopes.

At all three sites, deep soils were found on lower slopes and shallow soils on upper slopes (Figures 6.4a, 6.5a and 6.6a). This reflects a significant influence of slope position on soil depth and a general agreement with the previous hypothesis. However, at Batta upper slopes were marginally deeper than its middle slopes. As in the case of soil texture classes, the general relationship between slope position and soil depth is reversed on some slopes. For example Batta slope 10, Bayyada slope 7 and Lussaita slope 2 have soils that are deeper on their upper positions than the lower positions. This might be attributed to the small angle or increased vegetation cover on these parts; in both cases loss of material from upper slopes would be reduced or even prevented.

6.2.2.3 Organic matter content

As mentioned earlier, organic matter content is a soil property that is expected to increase downslope. However, as Figures 6.4b, 6.5b and 6.6b show, organic matter generally decreased downslope. This reversed relation in the three sites can be attributed to the influence of land use on organic matter content which is discussed below (section 6.2.3.3). This trend, however, was not uniform at Batta, where the lower slopes had a higher organic matter than the middle slopes. As with the Lussaita and Bayyada sites the lower slope areas of this site were mainly cultivated; however, their unusual relatively high percent of organic matter was most likely to be attributed to the high amount of straw mulch that covered the soil surface of these cultivated areas (see section 6.2.3.3). Straw mulching is reported to maintain or increase organic matter content (Greb et al., 1974 and Verity and Anderson, 1990).

6.2.2.4 Infiltration rate

At all three sites, the highest infiltration rates were found to be related to upper slopes and the lowest to lower slopes (Figures 6.4c, 6.5c and 6.6c). Like organic matter, this soil property showed an inverse relationship with slope position and soil depth. On the other hand, it was correlated positively with organic matter and significantly related to soil texture. Organic matter can influence infiltration by holding water on the soil surface long enough for it to enter the soil and by improving the soil physical conditions such as soil aggregation which in turn influence soil structure and water infiltration (Campbell, 1978). Coarse texture indicates high permeability. This reflects the influence of texture and organic matter through improved structural development on infiltration rate, and is an example of the complexity and contradiction found in the relationships of these factors.

6.2.2.5 Distribution of land use types by slope position

Wheat and barley areas are almost entirely restricted to the gentle lower and middle slopes (Table 6.3). In addition to accessibility and suitability for machine use, these areas usually have the deepest soils, and could be expected to receive

Lussaita site

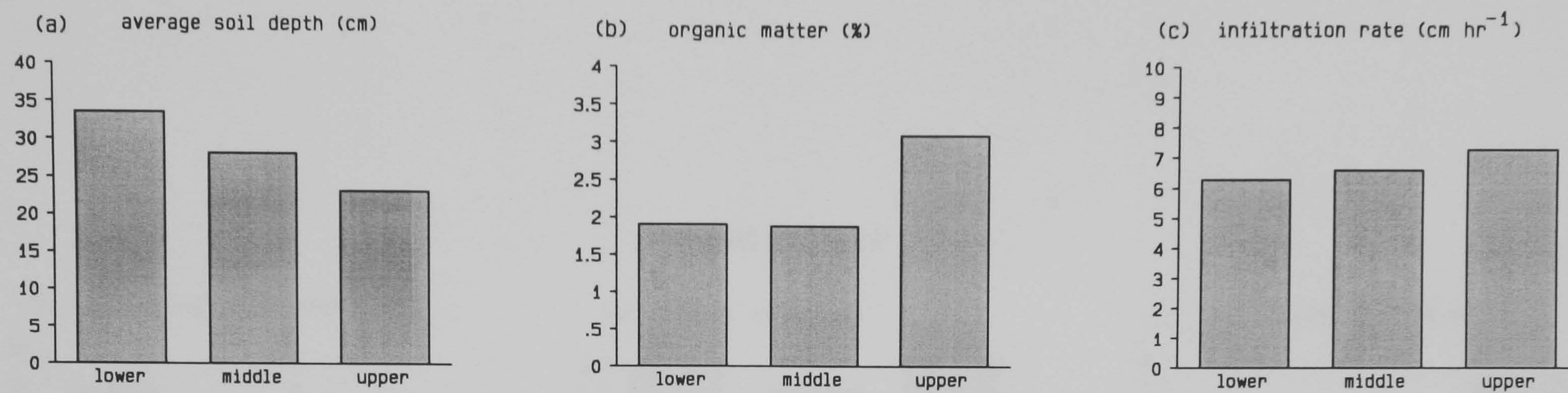


Figure 6.4 Mean soil properties by slope position

Bayyada site

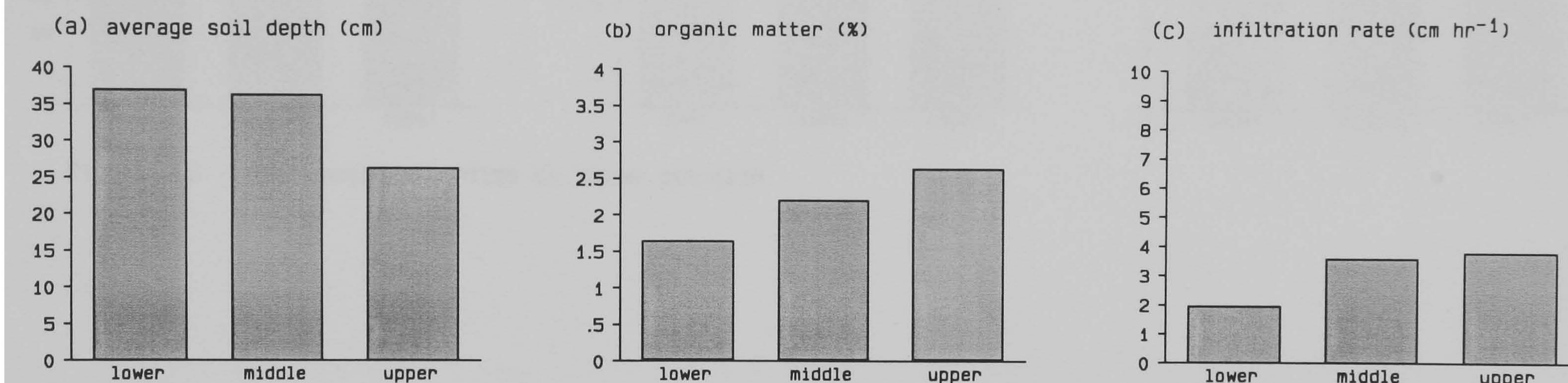


Figure 6.5 Mean soil properties by slope position

Batta site

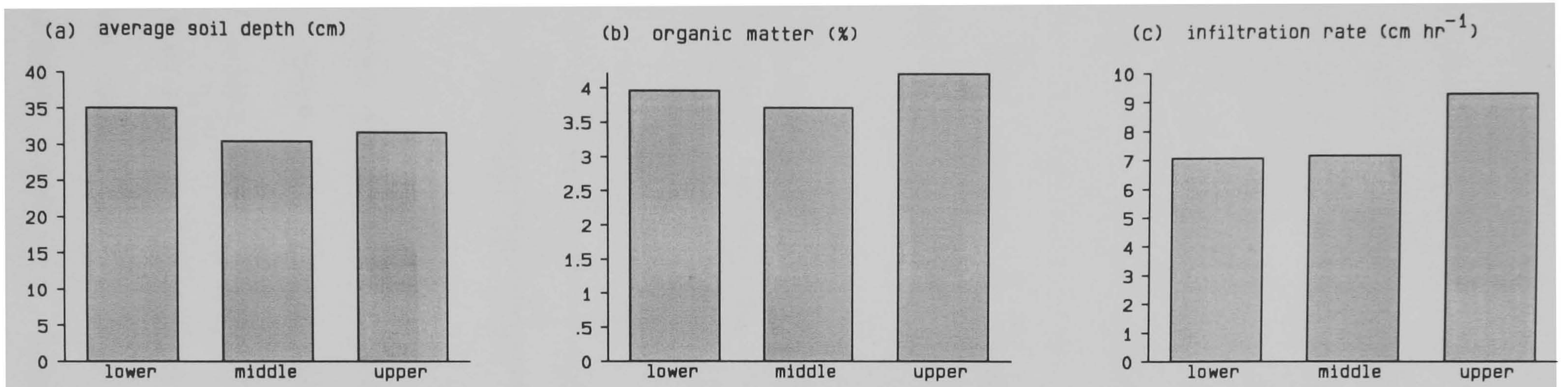


Figure 6.6 Mean soil properties by slope position

nutrients and possibly organic matter eroded from upper slopes plus additional plant-available water. Therefore, the yields of these positions are usually higher than that of middle and upper slope positions (Brubaker et al., 1993; Jones et al., 1989 and Pierson and Mulla, 1990). In contrast, natural vegetation areas are generally located on upper steep slopes where the soils are shallower. However, at Bayyada, some upper slope areas were cultivated and others were cleared prior to cultivation. The use of some upper slopes for cultivation at this site was due to a limited amount of lower slope land and to the much reduced gradient of the upper slopes thus making them more accessible for cultivation. This increase in agricultural activity at Bayyada is reflected in the fact that of the 30 cross profiles surveyed at this site, natural vegetation was recorded only four times.

Table 6.3 Distribution of land use types by slope position.

slope position	nat.vegn lu	nat.vegn by	nat.vegn bt	d/grass lu	d/grass by	d/grass bt	w/barley lu	w/barley by	w/barley bt	f/trees lu	f/trees by	f/trees bt	cleared lu	cleared by	cleared bt
lower	1	0	0	5	1	2	3	6	8	1	3	0	0	0	0
middle	2	1	4	5	1	2	0	4	4	3	3	0	0	1	0
upper	7	3	9	0	3	0	0	2	1	3	0	0	0	2	0
total	10	4	13	10	5	4	3	12	13	7	6	0	0	3	0

lu=Lussaita site by=Bayyada site bt=Batta

6.2.2.6 Distribution of soil erosion features by slope position

At the three sites, most of these features, especially gullies, were located on lower slope positions, with some rills and concentrated flow on the middle and upper slopes (Table 6.4). This gives an indication that, generally, more erosion has occurred on lower positions than on upper positions. This distribution pattern of soil erosion features was mainly attributed to the type of land use and the vegetation cover. At all the three sites, lower slopes were mainly areas of wheat and barley (see Table 6.3). Such areas are cultivated by machines, ploughing is up and down slope in most cases, and there is a lack of surface cover during the most critical period of the season (i.e. the beginning of the wet season). Therefore, these areas are found to be affected by all erosion features, in particular gullies. At some sites, however, the previous situation can be made worse by road construction. At Bayyada, for instance, a road built across the valley floor has forced the surface runoff to pass through a small gutter, and this concentrated water has contributed to the enlargement of the two gullies located on the lower positions of slopes 6 and 7 (Plates 6.2 and 6.3).

Table 6.4 Distribution of erosion features according to slope position.

slope	Lussaita			Bayyada			Batta		
position	gul.	ril.	cfl	gul.	ril.	cfl	gul.	ril.	cfl
lower	3	1	2	2	0	2	7	0	3
middle	0	0	3	0	5	0	0	3	1
upper	0	0	1	0	0	0	0	0	1

(for key see Table 6.1)

6.2.3 The relationships between soil properties and land use

There are four types of land use at Lussaita site, namely natural vegetation, dry grass, cereals (wheat and barley) and fruit trees. In addition to these four land use types, Bayyada has an extra category of land use which is cleared land. Batta has the same types of land use as Lussaita with the exception of fruit trees (Table 6.5). Most of the dry grass areas, however, are either areas cleared of natural vegetation and left uncultivated, or areas of wheat and barley stubble from the previous season.

Table 6.5 Frequencies and means of per cent cover by land use.

type of land use	Lussaita freq.	Lussaita pcc	Bayyada freq.	Bayyada pcc	Batta freq.	Batta pcc
nat.vegn	10	37.0	4	36.8	13	55.5
d/grass	10	25.2	5	27.2	4	44.3
w/barley	3	24.7	12	15.5	13	44.7
f/trees	7	46.6	6	23.5	0	0.0
cleared	0	0.0	3	7.7	0	0.0

nat.vegn=natural vegetation. d/grass=dry grass.
w/barley= wheat and barley. f/trees=fruit trees.
cleared=cleared land. pcc=per cent of vegetation cover.

Plate 6.2 An example of how road construction can alter surface runoff, concentrate it in a small area and, therefore, contribute to the enlargement of gullies, Bayyada site.

Plate 6.3 A closer view of the previous gully (Plate 6.2). Note, the trees are less than 30 years old.

6.2.3.1 Soil texture

At all three sites, areas of wheat and barley were associated with texture classes finer than those of natural vegetation (Table 6.6). The distribution of dry grass and fruit trees was less clear; however at most locations dry grass was on finer-textured soils and fruit trees on coarser-textured soils. These patterns appear to reflect the topographic position of the different land uses, with wheat and barley and dry grass areas, in Lussaita and Batta sites, and wheat and barley areas in Bayyada site, being located on lower slopes or valley floors where sedimentary accumulation of fine materials is active.

Table 6.6 Summary of results, showing relationships between soil properties and land use.

(a) Lussaita site.

type of land use	c	tc	cl	tcl	tl	l	scl	sl	SD (cm)	OM (%)	IR cm hr^{-1}	pcc (%)
nat.vegn	3	1	0	2	3	1	0	0	21.5	2.8	6.6	37.0
d/grass	5	1	2	1	1	0	0	0	33.0	1.9	6.0	25.2
w/barley	2	0	1	0	0	0	0	0	31.6	2.0	5.5	24.7
f/trees	2	1	1	3	0	0	0	0	29.9	2.3	8.2	46.6
t/mean	12	3	4	6	4	1	0	0	28.3	2.3	6.6	34.1

(b) Bayyada site.

type of land use	c	tc	cl	tcl	tl	l	scl	sl	SD (cm)	OM (%)	IR cm hr^{-1}	pcc (%)
nat.vegn	0	0	2	0	0	1	1	0	21.2	3.5	4.3	36.8
d/grass	0	0	0	2	0	2	1	0	33.4	2.6	3.2	27.2
w/barley	0	0	2	6	2	2	0	0	36.7	1.8	2.9	15.5
f/trees	0	0	0	3	2	1	0	0	36.6	1.6	2.3	23.5
cleared	0	0	1	1	1	0	0	0	28.1	1.5	3.5	07.7
t/mean	0	0	5	12	5	6	2	0	33.2	2.1	3.1	21.1

(c) Batta site.

type of land use	c	tc	cl	tcl	tl	l	scl	sl	SD (cm)	OM (%)	IR cm hr^{-1}	pcc (%)
nat.vegn	0	0	4	6	1	2	0	0	31.7	4.3	8.2	55.5
d/grass	0	0	2	1	0	0	0	1	16.8	3.2	6.5	44.3
w/barley	0	0	3	10	0	0	0	0	38.1	3.9	7.6	49.2
t/mean	0	0	9	17	1	2	0	1	32.5	4.0	7.7	49.3

(for key see Tables 6.2 and 6.4)

6.2.3.2 Soil depth

The relationship between soil depth and land use type is essentially influenced by the location of each land use type according to slope position. Those located on lower slopes (cereals and dry grass) are usually associated with soils deeper than those of upper slopes. On the shallower soils of the upper slopes, with the exception of Bayyada, land use is dominated by natural vegetation (Figures 6.7a. 6.8a and 6.9a).

6.2.3.3 Organic matter

At all three sites, natural vegetation is associated with the highest organic matter content, with a mean that is higher than the overall mean for each site (Figures 6.7b, 6.8b and 6.9b). This is probably a result of a combination of high organic matter input and the extensive leaf cover which protects the soil from high temperatures that lead to faster decomposition rates; thus the final result is an increase in organic matter content (Kern and Johnson, 1993; Van Wambeke, 1992). As fruit trees behave in a similar way to the natural vegetation they too have a similar effect on soil organic matter as can be seen in Table 6.6.

At both Lussaita and Batta, the lowest organic matter contents were related to areas of dry grass and wheat and barley cultivation. This reduction in organic matter content is attributable to cultivation processes which increase the rate of organic matter decomposition by oxidation, whilst the removal of most of the crop, both grain and straw, reduces greatly the amount of organic matter returned to the soil by wheat and barley residues (Goldin and Lavkulich, 1990).

At Bayyada, the lowest organic matter was recorded under cleared rather than land under cereal cultivation. This can be attributed to the method of clearance used, in which bulldozers are used to clear the vegetation and in so doing not only remove

Lussata site

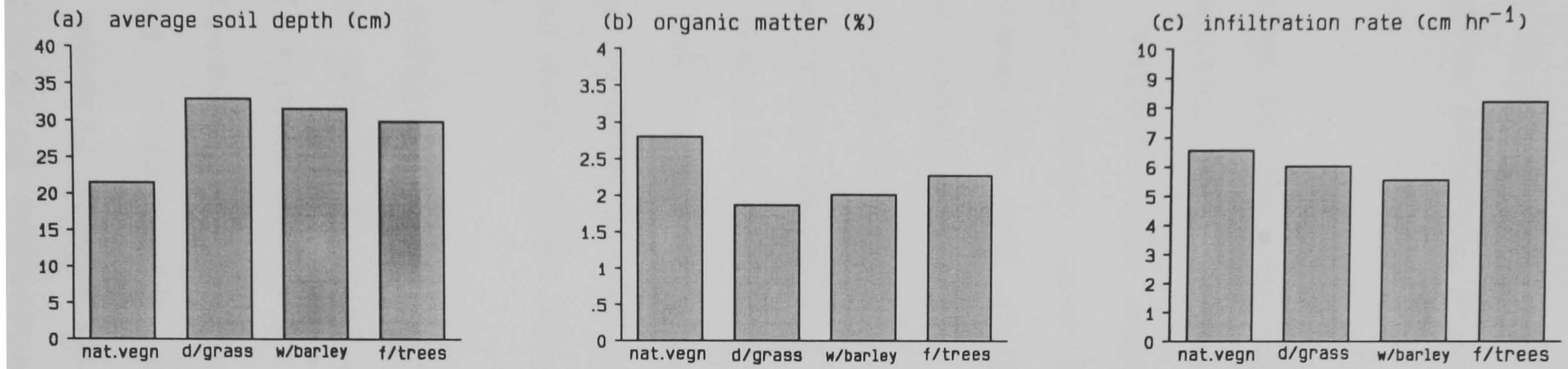


Figure 6.7 Mean soil properties by land use

Bayyada site

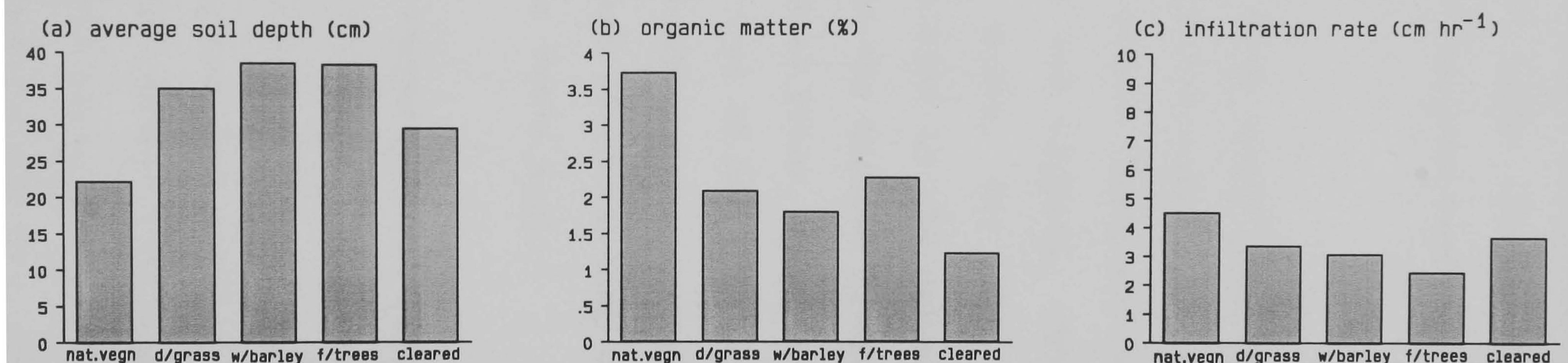


Figure 6.8 Mean soil properties by land use

vegetation and logs but also some of the topsoil which contains most of the organic matter. The remaining exposed subsoil is much less fertile and contains little organic matter. The long-term result is a potential loss of crop production (Ghuman et al., 1974; Jones et al., 1989 and Sanchez, 1981). During the field study, complete scraping and piles of topsoil were observed at this site.

In addition to the similarity in high organic matter under natural vegetation, the three sites are also similar in recording low organic matter under cultivated areas. Batta has recorded higher organic matter than Lussaita and Bayyada, under both natural vegetation and cultivated areas, for the reasons mentioned in section 6.2.2.3. In addition to the general high percent of vegetation cover, Batta has the highest frequency of natural vegetation, which was recorded 13 times, while it was 10 in Lussaita and 4 in Bayyada. In the case of the few cultivated areas which have higher than average organic matter content, this was probably related to the high amount of straw that was left in cultivated areas after harvest (see Table 6.5).

Organic matter can be exhausted through total removal of vegetation as crop or through grazing (Kirkby, 1980). Therefore, the level of organic matter on each slope position in cultivated areas is influenced by the amount of straw left on soil surface after harvest. This level of organic matter on each slope position in natural vegetation areas is also influenced by the intensity of grazing and percent of vegetation cover. At Batta,

Batta site

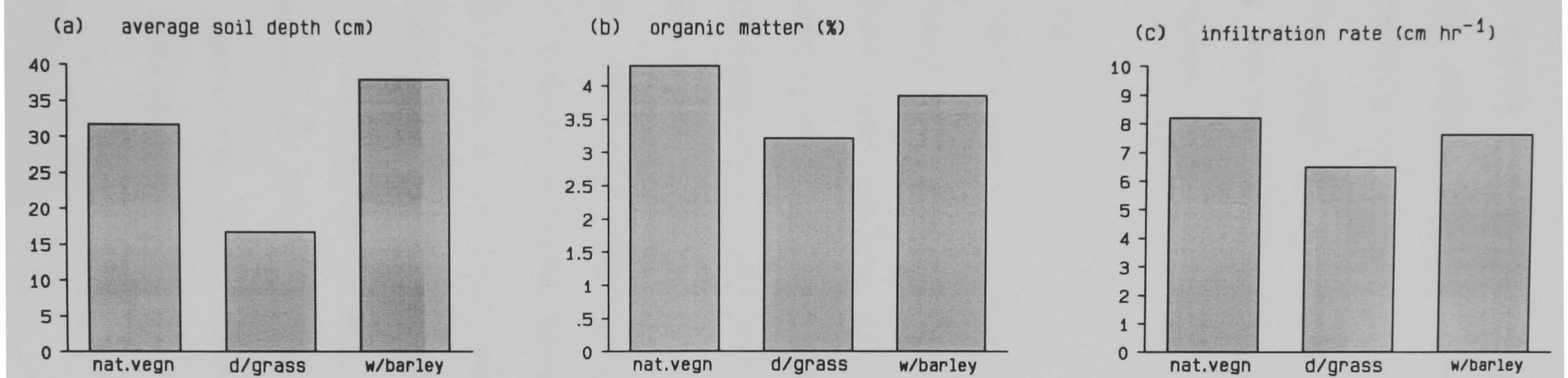


Figure 6.9 Mean soil properties by land use

the amount of straw left in cultivated areas was relatively high and its natural vegetation cover recorded the highest percent in all six sites (Table 6.6c). Added to these, no grazing activities were noticed during the field study. In addition, the natural vegetation cover at Batta comprises mainly Klil shrubs (*Rosmarinus officinalis*); these shrubs are generally dense and characterised by a relatively thick surface litter. As explained earlier in this section, such cover increases organic matter input and slows organic matter decomposition by protecting the soil from high temperatures.

6.2.3.4 Infiltration rate

In the three sites, the highest infiltration rate means were recorded under natural vegetation and fruit trees and the lowest under dry grass and wheat and barley (Figures 6.7c, 6.8c and 6.9c). These results clearly reflect the effect of high organic matter content and coarse texture on infiltration rates. However, the infiltration rate of fruit tree areas in Lussaita site was higher than that of the natural vegetation, even though the former had lower organic matter content than the latter. This is probably due to the difference in soil depth between the two types of land uses. In Bayyada, cleared areas have low organic matter content and high infiltration rates. This might be due to the fact that the remains of cleared vegetation, especially roots, facilitated the vertical movements of water and hence increased the rates of infiltration.

6.2.3.5 Soil surface characteristics

At Lussaita, crusting was recorded mainly under natural vegetation and dry grass (Table 6.7a). However, cultivated areas were free of crust almost certainly because of the activities of land preparation, especially ploughing. Fieldwork was undertaken after cultivation and before the beginning of the rainy season, and a surface crust would be expected to start forming after the first rain.

Table 6.7 Frequencies of soil surface characteristics and percent of cross-profile covered by bare ground, stones and exposed outcrop by land use.

type of land use	no. of c.p.	frequency of comp.	crack	crt	ert	% of c.p. covered by b/grd	stn	oce
(a) Lussaita site.								
nat.vegn	10	2	3	5	2	21	18	7.5
d/grass	10	1	8	2	0	45	24.5	1
w/barley	3	0	1	0	0	38.3	18.3	0
f/trees	7	3	2	0	0	63.6	12.9	0
(b) Bayyada site.								
nat.vegn	4	0	0	3	1	25	38.8	8.8
d/grass	5	0	2	2	0	25	32	0
w/barley	12	4	2	2	1	45	27.1	0
f/trees	6	3	4	3	0	21.7	9.4	0
cleared	3	1	0	0	0	33.3	55	0
(c) Batta site.								
nat.vegn	13	1	3	5	1	21.2	20.8	2.3
d/grass	4	2	1	0	0	56.3	25	0
w/barley	13	1	4	3	2	50.4	23.5	0

c.p.=cross-profile comp.=compaction crack=cracks. crt=crust. ert=exposed roots. b/grd=bare ground. stn=stone. oce=outcrop exposure.

Soil compaction, one of the characteristics of this soil, was found to be related to natural vegetation and fruit trees, with cultivation appearing to reduce compaction. Cracking is another characteristic of this soil. Cracks were recorded under each land use. However, the highest density of cracks was related to dry grass, which might be due to the fact that clayey texture was the dominant in the dry grass areas and to the reduced shade which increases drying.

Stone cover plays a very important role in preventing soil erosion by water. This cover protects the soil surface from raindrop impact and increases infiltration rate as water flows into the soil around the edges of the stones (McIntyre, 1958 and Poesen et al., 1990). In the studied sites, this cover was expected to be higher in natural vegetation areas than those cultivated mainly because collecting stones is usually part of preparing lands for cultivation. Whilst this was true for Lussaita, both Bayyada and Batta had higher stone cover in cultivated rather than naturally vegetated areas. This is mainly due to the fact that only large stones, which may form obstacles during ploughing, are collected. In addition, most of these soils contain stones below their surface; thus, stones are usually added to the surface by ploughing.

In Bayyada, most of the compaction was recorded under cultivated areas, partly as a result of the machinery used in cultivation (Table 6.7b). Crusting was recorded under all types of land use except that of cleared cultivated land. Like Lussaita, cracking in this site was found to be related to cultivated and dry grass areas. Natural vegetation areas, due to their location on upper slopes, have recorded the highest percent of outcrop exposure. Wheat and barley and dry grass areas recorded the highest percent of stone cover. It seems that fruit trees and cereals areas were the most affected by compaction, crusting and cracking. This might be attributed to the fine textures and low organic matter content that characterized these areas.

At Batta, very few cases of compaction, crusting and cracking were recorded (Table 6.7c). This can be attributed to two key factors, namely the generally lower clay content, and the higher organic matter of the soils at this site. (The lowest amount of organic matter recorded at this site was 3.2% and the finest texture was clay loam with the complete absence of clay texture at this site). The combination of these two factors contributes to a more stable surface structure resistant to crusting and hence having a high infiltration rate.

6.2.3.6 Distribution of soil erosion features

At all the three sites, most of the recorded features of erosion are located in cultivated areas, especially wheat and barley (Table 6.8). These cultivated areas are generally characterised by fine textures, low organic matter content and low infiltration rates.

Table 6.8 Frequency of erosion features by land use.

type of land use	no. of	Lussaita gul.	Lussaita ril.	Lussaita cfl	Bayyada gul.	Bayyada ril.	Bayyada cfl	Batta gul.	Batta ril.	Batta cfl
nat.vegn		0	0	1	0	1	0	0	2	1
d/grass		1	1	5	0	1	0	0	0	0
w/barley		1	0	0	1	3	2	7	1	4
f/trees		0	0	0	1	0	0	-	-	-
cleared		-	-	-	0	0	0	-	-	-
total		2	1	6	2	5	2	7	3	5

(for key see Table 6.1)

6.3 Magra site

The Magra site is located in the southern part of the first (lower) bench, at the foot of the second escarpment. Topography in this site consists of an undulating plateau dissected by steep-sided valleys coming from the second (upper) bench. Thus, most of the lower and some middle parts of the slopes of these valleys are so steep that they are still covered with natural vegetation; any cultivation takes place on the upper slopes, i.e. the plateau surface (see profiles 3, 4 and 5 on Figure 6.10a). However, where valleys originate on the first bench surface, then these are less deeply incised and are characterised by gentle lower slopes, which can be used for cultivation (see profiles 1 and 2 on Figure 6.10b). Because of these differences in the distribution of land use types according to slope position, the slopes of Magra site were divided into two groups. These are:group 1, comprising 6 slopes, 3, 4, 5, 6, 8, and 9, group 2 comprising 4 slopes, slopes 1, 2, 7 and 10. The slopes of group 1 have natural vegetation on their lower slopes and their upper slopes are cultivated, whilst the reverse is true for group 2 slopes.

6.3.1 Topographic relationships

From this description, it appears that some of the slope characteristics of this site are very different from those at the previous three sites. The principal differences are the distribution of erosion features and their relation to slope length and steepness (Table 6.9 and Figures 6.10a and b). These features were recorded on 6 slopes. In addition to rills and

Table 6.9 Slope profile measurements and soil erosion features.

	slope profile number	L (metres)	ST (degrees)	number of gul.	rill.	cfl
group 1	3	259	6.9	2	1	1
	4	363	7.4	0	0	0
	5	320	15.1	1	1	1
	6	379	4.4	0	0	0
	8	264	3.5	1	1	1
	9	477	8.3	1	1	0
group 2	1	291	4.3	1	0	0
	2	226	3.2	0	0	0
	7	373	3.9	0	0	0
	10	431	4.9	1	2	3

(for key see Table 6.1)

concentrated flow, each slope recorded one gully, except slope 3 where two gullies were recorded. However, the most affected was slope 3, a 6.9° and a 259 metre slope (Figure 6.11). Slope 5, a 15.1° slope, the steepest at this site, also showed the three types of erosion features, and therefore is considered as one of the most affected slopes. The two longest slopes at this site, slopes 9 and slope 10, were also affected by erosion. Here however the features were concentrated in the vicinity of a recently constructed road. This road collected surface runoff and concentrated it into a small gutter from where it spread out, causing considerable erosion, especially gullying and concentrated flow. From the sediments that covered some parts of this road, which were still visible during the field study, it seemed that during heavy rain events, the water accumulated behind the road before flooding across it. A similar feature was mentioned previously at the Bayyada site, and from both cases it appeared that this problem could be limited if the road was constructed to follow the topography. In conclusion, the

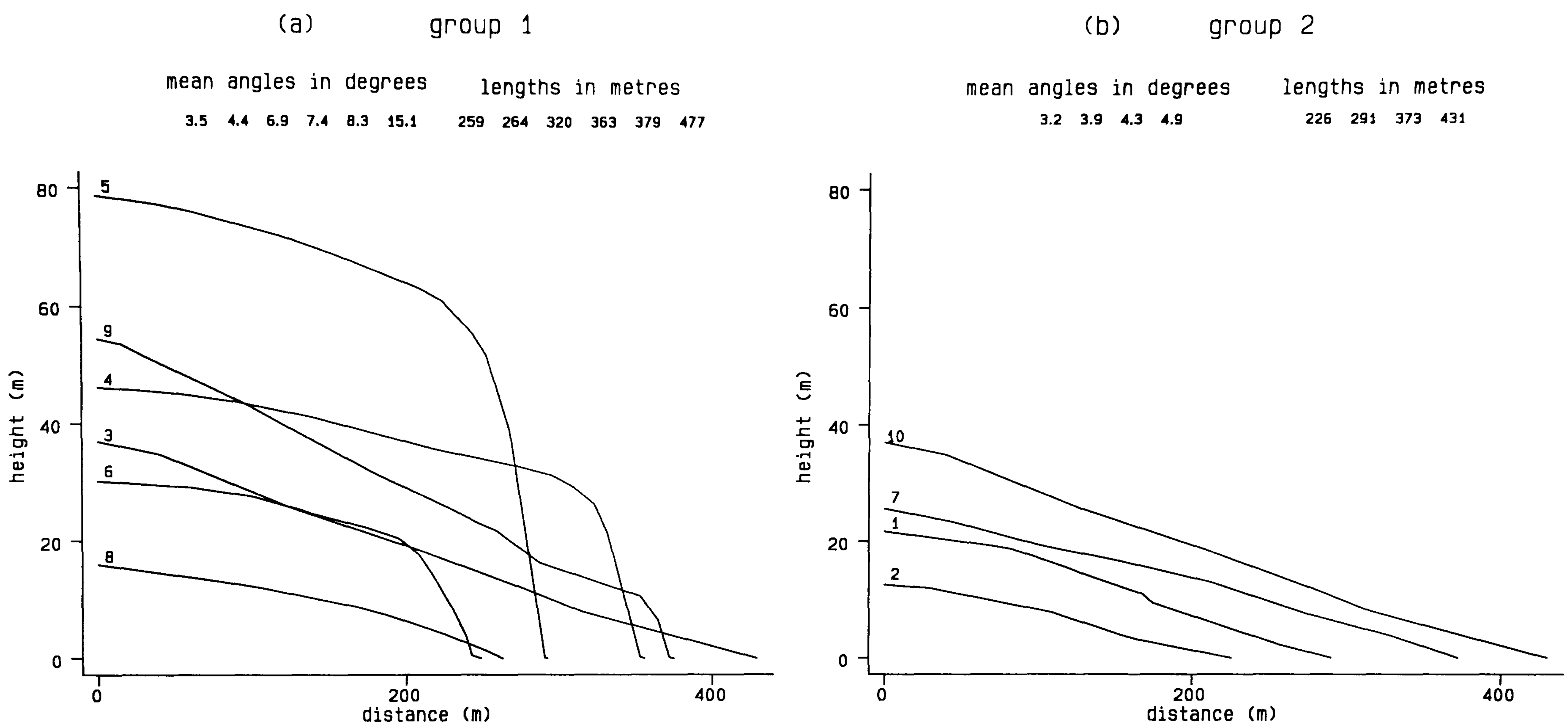


Figure 6.10 Magra slope profiles

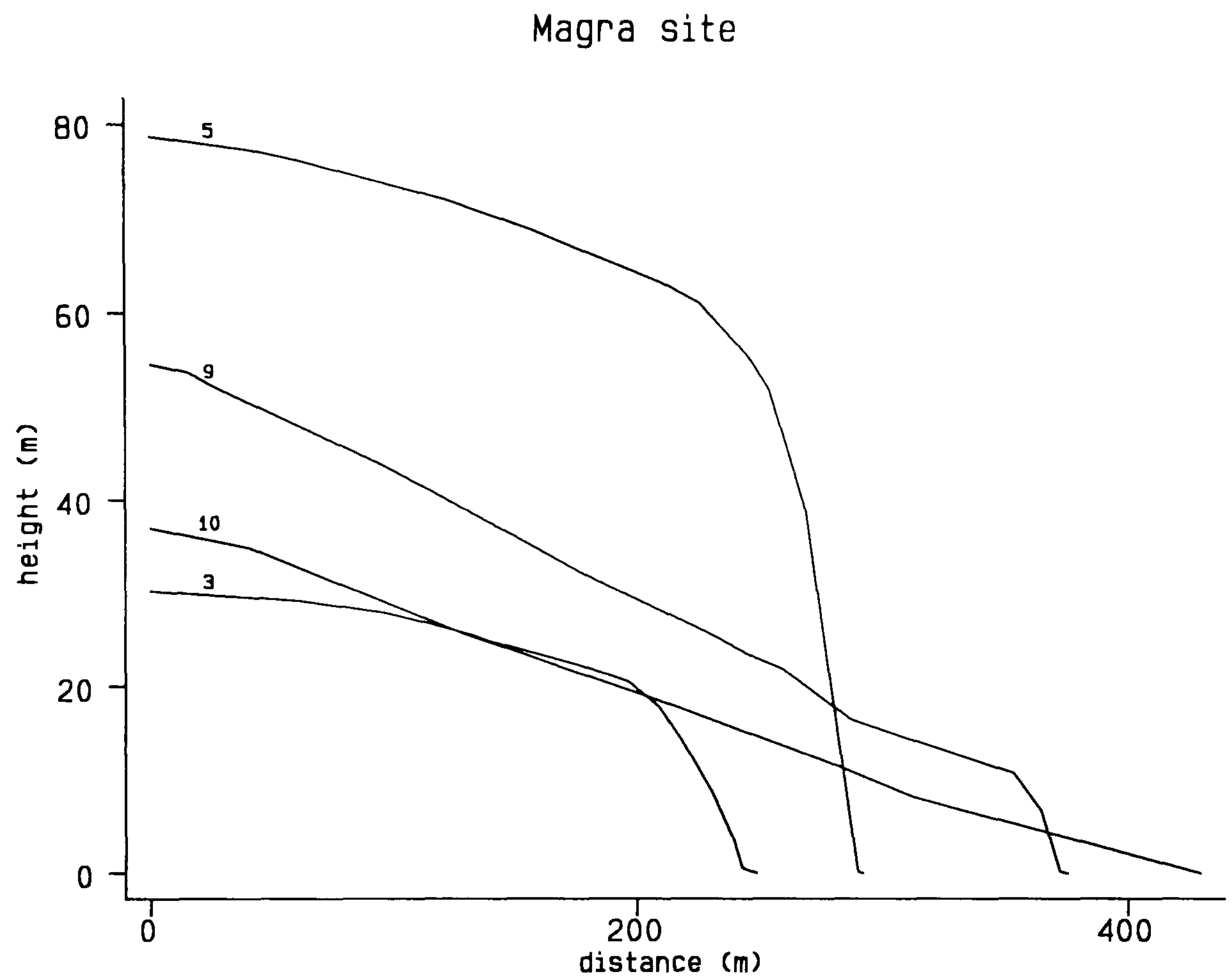


Figure 6.11 The most eroded slopes

relationship between slope length and steepness and erosion features was not completely clear: generally, the most affected slopes in the two groups are comparatively long and steep.

6.3.2 The relationship between soil properties and slope position

6.3.2.1 Soil texture

The slopes of Magra recorded the highest clay texture in the study area (Tables 6.10a and b). Out of the thirty soil samples analyzed for particle size distribution at this site, 16 were classified as clay and 8 were silty clay. In group 1, these textural classes were distributed as 1 on the lower, 5 on the middle and 6 on the upper slopes. This distribution of fine texture showed a reverse relationship with slope position compared with the previous 3 sites. The positions with the coarsest textures, silty clay loam, were limited to lower slopes of group 1 and lower and middle slopes of group 2. The explanation appears to be linked to slope angle and vegetation cover: the upper slopes are more gentle than many of the lower slopes; hence there is limited erosion of fine material for deposition downslope. Conversely the lower slopes are steeper and have a poorer vegetation cover, thus fines will be removed from the soil leaving coarser textures on the foot slopes (Webster, 1965).

6.3.2.2 Soil depth

For group 1 slopes, the mean soil depths for the different positions of slope were close at this site (Figure 6.12a). As with the pattern of soil texture, the relationship between slope position and depth is the reverse of the previous 3 sites. The lower slopes tending to have shallower soils than either the upper or middle slopes, the soils of the middle slopes however tended to be deeper than either. Thus the general pattern is one of soil depth decreasing downslope. This mainly is attributed to the steepness and the poor vegetation cover of these lower slopes. In contrast, on group 2 slopes, soil depth showed a good relationship with slope position, i.e. increasing down slope (Figure 6.13a). This is mainly due to the marginally less steep and more vegetated lower slopes of this group, and the accumulation of eroded material from upper slopes.

Table 6.10
Frequencies of texture classes and means of soil properties, angles and per cent vegetation by cover by slope position.

(a) group 1

slope position	texture class. c	tc	cl	tcl	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc %
lower	1	1	1	3	19.5	1.7	2.8	5.0	19.3
middle	5	1	0	0	21.0	1.7	2.4	4.7	25.2
upper	6	0	0	0	20.0	2.3	3.3	3.3	31.3
(b) group 2									
lower	1	0	1	2	26.4	2.7	2.7	4.5	27.0
middle	2	0	0	2	25.6	2.4	4.1	4.9	25.8
upper	1	0	2	1	20.7	2.6	2.9	3.0	25.5

(for key see Table 6.2)

6.3.2.3 Organic matter

In group 1, although land use distribution according to slope position is the opposite to that of group 2 and the previous three sites, the relationship between organic matter and slope position was the same as the previous sites, i.e. decreasing downslope (Figure 6.12b). Overall levels were however much lower.

Group 1

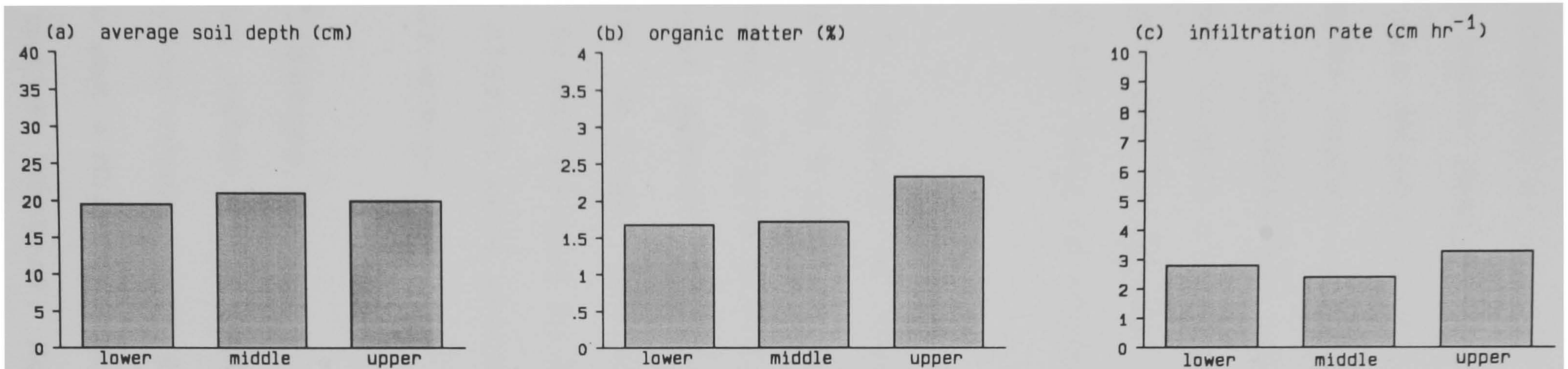


Figure 6.12 Mean soil properties by slope position

Group 2

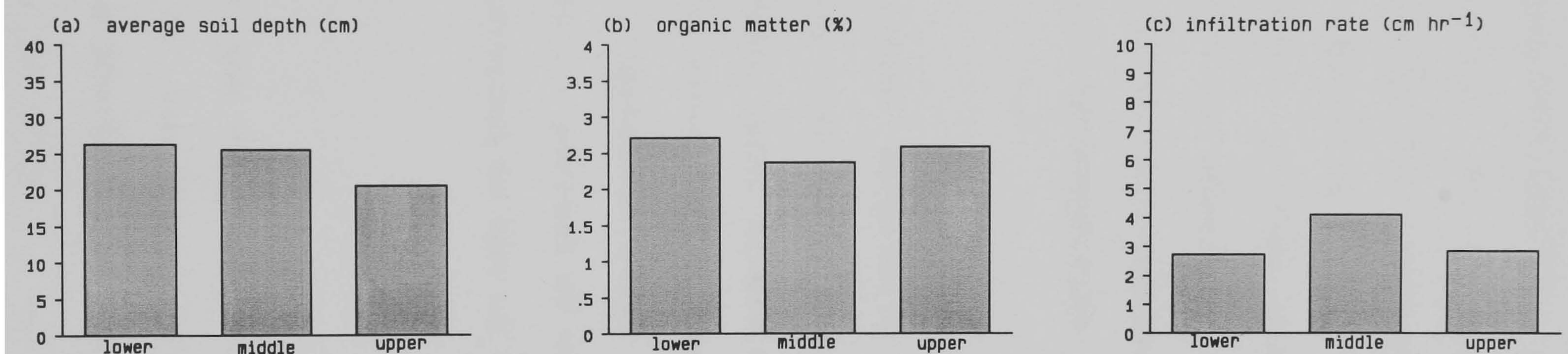


Figure 6.13 Mean soil properties by slope position

The highest was related to upper slopes. This probably is due to the fact that on the lower slopes of this group, even though they are naturally vegetated, the cover is very poor and affected by heavy grazing. In addition, these lower parts are steep, therefore, erosivity of runoff will increase, and fine particles as well as organic matter will be removed. On the other hand, upper parts are mainly cultivated areas, but these parts are gentle and have higher percents of vegetation cover than the lower slopes. Furthermore, the increase of clay and organic matter on upper slopes of group 1, which are erosional areas, is assumed to be a result of the formation of clay-organic complex which reduces the rate of organic matter decomposition (Stone et al., 1985).

In group 2, values of organic matter marginally increase downslope and show a good relationship with slope position and vegetation cover (Figure 6.13b). However, upper slopes appear to have the lowest percent of vegetation cover while the mean of organic matter is high. The mean of vegetation cover of these upper slopes is pulled down by the very low percent of vegetation cover of the cleared area which was recorded on one of the upper slopes of this group.

6.3.2.4 Infiltration rate

Infiltration rates were generally low in both groups. The overall rate for group 1 was 2.8 cm hr^{-1} and was 3.2 cm hr^{-1} for group 2. This was a direct result of a dominant clay texture and low organic matter content. However, in group 1, infiltration rate decreases marginally downslope as a result of organic matter influence and hence weaker, less developed structures (Figure 6.12c). On the other hand, this relationship between slope position and infiltration rate is not clear in group 2. Whilst the lower slopes have lower rate of infiltration than the upper slopes, the rate of the middle slopes is higher than either (Figure 6.13c). The mean infiltration rate for the upper slopes of this group was pulled up by the high rate of the cleared area, which was recorded on the upper position of slope 2. While the mean infiltration rate of the middle slopes was pulled up by a higher than usual rate of infiltration that was recorded on the middle position of slope 1, an area of vine trees, its soil was recently loosened probably as a part of land preparation before the rainy season.

6.3.2.5 Soil erosion features

Unlike other sites, Magra erosion features were recorded on all slope positions of both groups (Table 6.11). However, the concentration of these features, gullies in particular, was on the upper and middle slopes of group 1 and mainly on the lower slopes of group 2. This might be a result of using these slope parts for cultivation.

Table 6.11 Distribution of soil erosion features according to slope position.

slope position	group 1 gul.	ril.	cfl	group 2 gul.	ril.	cfl
lower	0	0	1	1	0	1
middle	4	2	1	0	1	1
upper	1	2	1	0	1	1

(for key see Table 6.1)

6.3.3 The relationship between soil properties and land use

6.3.3.1 Types of land use

As Table 6.12 shows, natural vegetation and fruit trees are the dominant types of land use in group 1, recorded 7 and 6 times respectively. Fruit trees and wheat and barley are the dominant types of land use in group 2, recorded 5 and 3 times respectively. Cleared land was recorded only once in group 2.

Table 6.12 Slope position and type of land use.

group no.	slope position	frequency of each type of land use nat.vegn	d/grass	w/barley	f/trees	cleared
group 1	lower	5	1	0	0	0
	middle	1	1	0	4	0
	upper	1	1	2	2	0
group 2	lower	0	2	1	1	0
	middle	1	0	1	2	0
	upper	0	0	1	2	1

(for key see Table 6.4)

6.3.3.2 Soil texture

In both groups, fruit tree area recorded the highest frequency of clay textures, whilst natural vegetation of group 1 and dry grass and cereals of group 2 recorded the highest frequency of coarse texture (silty clay loam) (Table 6.13). In both cases and in both groups, this was related to the location of each land use according to slope position. The land uses located on upper slopes have finer textures than those located on lower slopes.

6.3.3.3 Soil depth

The overall mean of soil depth in group 1 was 20.2 cm, and 24.2 cm in group 2. The soils of group 1 are shallow as a result of its steep and less vegetated lower slopes (Figure 6.14a). However, the averages of soil depths differ little between land use types of this group. The deepest soil was 20.8 cm found under fruit trees, and the shallowest was 17.9 cm found under wheat and barley. The naturally vegetated areas, although located on lower slopes, were relatively shallow, the overall mean being 20.1 cm, which is slightly less than the overall mean of this group which was 20.2 cm.

Table 6.13 Frequencies of soil texture classes and means of soil properties and per cent cover by land use.

(a) group 1

type of land use	text. classes c	tc	cl	tcl	SD (cm)	OM (%)	IR cm hr^{-1}	pcc (%)
nat.vegn	2	1	1	3	20.1	1.9	2.8	21.3
d/grass	3	0	0	0	20.4	1.3	2.9	20.7
w/barley	2	0	0	0	17.9	2.2	3.5	30.5
f/trees	5	1	0	0	20.8	2.1	2.6	30.5

(b) group 2

nat.vegn	1	0	0	0	20.4	2.4	2.4	28.0
d/grass	0	0	0	2	25.6	2.6	2.9	29.0
w/barley	0	0	1	2	29.6	1.7	3.5	12.7
f/trees	3	0	1	1	22.8	3.3	3.2	36.4
cleared	0	0	1	0	16.4	1.5	4.0	07.0

(for key see Table 6.6)

Group 2, because its slopes are gentle and have, relatively, good vegetation cover, especially on their lower positions, has deeper soils than group 1. The deepest soil in this group was 35.4 cm found under wheat and barley and the shallowest was 15 cm found under fruit trees (Figure 6.15a). However, if we exclude the cleared lands, the average soil depths differ little between the other land use types of this group.

6.3.3.4 Organic matter

This soil property is generally low at this site, especially in group 1, with an overall mean of 2.6%. However, the highest organic matter, in both groups, was related to fruit trees rather than natural vegetation (Figures 6.14a and 6.15a). Fruit trees, in most sites, showed relatively high organic matter, especially when dense and located on gentle slopes. In wheat and barley areas it was the amount of straw that affects the values of organic matter. On the other hand, natural vegetation of this site, especially in group 1, has generally poor cover, being both heavily grazed and located on the steep parts of the slopes; thus, they recorded low organic matter (Plate 6.4). The lowest organic matter was related to cleared lands, group 2. As in Bayyada site, this can be attributed to the methods of clearing.

6.3.3.5 Infiltration rates

Like soil depth, apart from under cleared land the infiltration rates at this site were similar, ranging from 2.4 cm hr^{-1} under natural vegetation to 3.5 cm hr^{-1} under cereals. Cleared areas had the highest rates of 4 cm hr^{-1} (Figures 6.14c and 6.15c). The relationship between infiltration rates and land use is unlike at the other sites far from clear, e.g. the cleared area which had the highest infiltration rate was also the shallowest and had the lowest organic matter content. Thus there seems little pattern, other than some possible link between land disturbance, cultivation and higher infiltration rates.

Plate 6.4
A steep slope where ground litter associated with trees is completely absent as a result of heavy grazing. Such areas produce high runoff, which in addition to removing much of the soil and exposing bedrock, also affect lower slopes, some concentrated flow is developed (foreground), Magra site.

6.3.3.6 Soil surface characteristics

Compaction, like surface crusting, was expected to be greater under cultivated areas due to the use of machines in cultivation. It appears that some cultivated ares were free of compaction as a result of deep ploughing. In both groups, compaction was recorded under all types of land use (Table 6.14). The highest was under dry grass natural vegetation and fruit trees in group 1, and under dry grass in group 2. Natural vegetation areas of group 1 are mainly areas of fine soils and low organic matter content. The high frequency of compaction in the fruit tree areas can be attributed to the use of machinery for irrigation during the summer months and the harvesting of the fruits. In all cases, machines usually pass between the trees, compacting the soil along these tracks (Hill and Meza-Montalvo, 1990). In some locations, these tracks developed into areas of concentrated flow or gullies.

Table 6.14 Frequencies of soil surface characteristics and percent of cross-profile covered by bare ground, stones and exposed out croup by land use.

group no.	c.p. no.	type of land use	Frequency of comp.	crack	crt	%of c.p. covered by b/grd	stn	oce
group 1	7	nat.vegn	3	1	2	43.6	22.1	2.1
	3	d/grass	2	3	0	56.7	16.7	1.7
	2	w/barley	1	2	0	32.5	37.5	0
	6	f/trees	3	1	1	7.8	15	0
group 2	1	nat.vegn	0	0	1	50	15	0
	2	d/grass	2	2	0	52.5	20	2.5
	3	w/barley	1	1	0	58.3	8.3	1.7
	5	f/trees	1	0	0	65	17	0
	1	cleared	1	0	0	66.5	35	0

(for key see Table 6.7)

Like compaction, cracks have been recorded under all types of land use except cleared land. However, in both groups, like Lussaita site and probably for the same reasons, dry grass and cereal areas were the most affected areas. Also, like Lussaita site, surface crusting was mainly found under natural vegetation.

Group 1

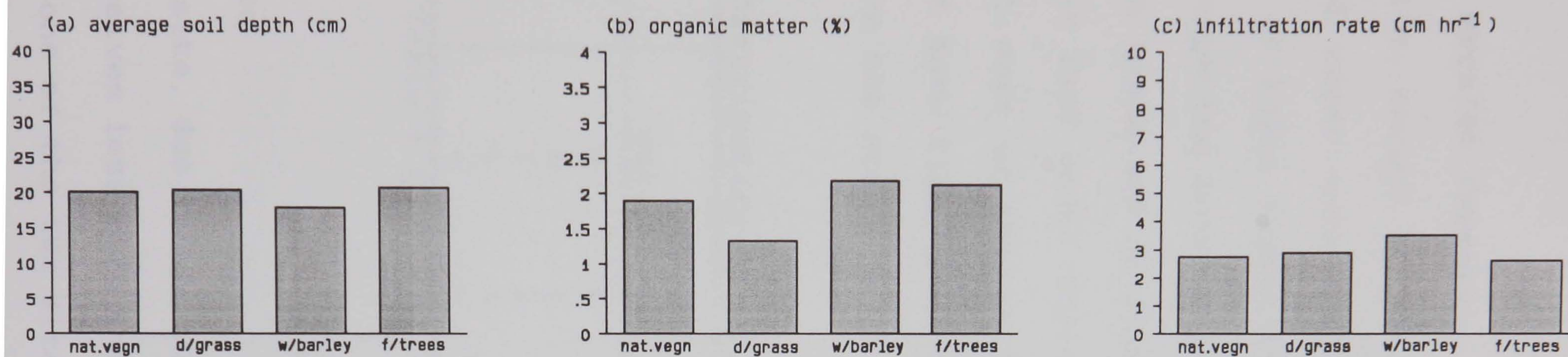


Figure 6.14 Mean soil properties by land use

Group 2

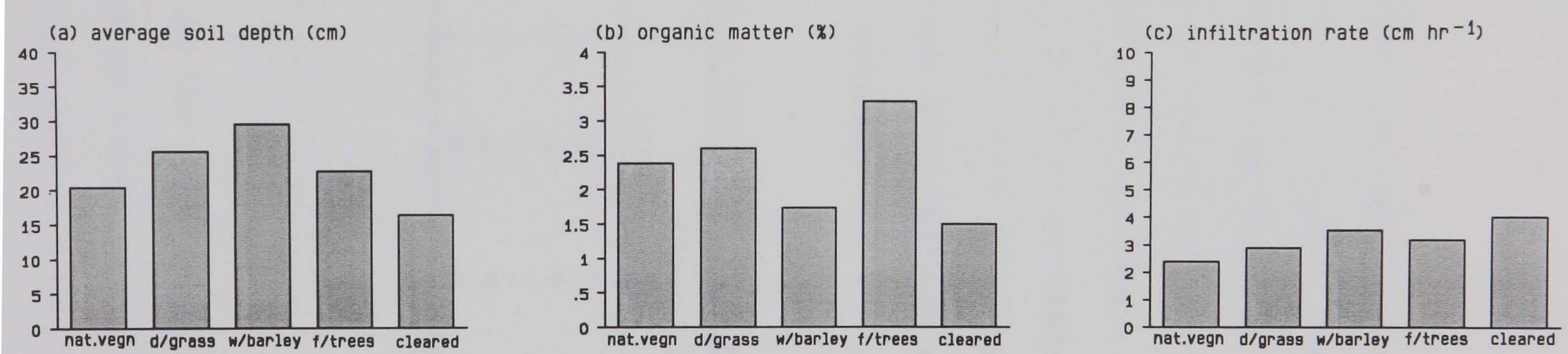


Figure 6.15 Mean soil properties by land use

The highest frequency of outcrop exposure was found to be related to natural vegetation areas of group 1, and dry grass of group 2. These areas, of both groups, are mainly found on lower slopes where the soils are generally shallow.

6.3.3.7 Soil erosion features

At this site, except in cleared lands, soil erosion features were recorded under each type of land use (Table 6.15). The distribution of these features however differs between groups. As is to be expected both groups have a concentration of these features under grass and cereals; the greatest incidence in group 1 sites was in fact under fruit trees. This was probably due to the fact that most of the soils of these fruit tree areas are compacted and have fine textures and low infiltration rate and are located on the steep parts of the slopes.

Table 6.15 Distribution of soil erosion features by land use.

type of land use	group 1			group 2		
	gul.	ril.	cfl	gul.	ril.	cfl
nat.vegn	0	1	1	0	0	0
d/grass	1	1	1	1	0	0
w/barley	1	1	0	1	2	3
f/trees	3	1	1	0	0	0
cleared	-	-	-	0	0	0

(for key see Table 6.8)

6.4 Gobba site

The Gobba site, due to its location in the eastern part of the Al-Jabal, receives less rain than the other sites. Gobba, as with Shahhat, was one of the two sites studied which had two distinct soil types, namely vertic brown, which is the soil type on 9 of the slopes, and ferric red, which is the soil type on the remainder. The vertic brown soil is characterised by swelling during the wet season and severe cracking during the dry season (Plate 6.5). Another character of this site was the absence of natural vegetation, as all the slopes studied were cultivated.

Plate 6.5 Wide and deep summer cracks in the vertic brown soil of Gobba site.

Furthermore, Gobba was the only site where irrigation was used to cultivate vegetables, water being pumped from deep wells located in each farm, and distributed to irrigated areas via channels.

6.4.1 Topographic relationships

As Table 6.16 shows, no significant erosional features were recorded at this site. The slopes of this site are comparatively gentle, the steepest being 5.5° and the gentlest 2.7° (Figure 6.16). In addition to the small amount of rain that this site receives (389.4 mm), the existence of deep and wide cracks plays a very important role in absorbing the rain at least at the beginning of the season. Combining these characteristics, the Gobba site had the least evidence of erosion of the 6 sites.

Table 6.16 Slope profile measurements and soil erosion features.

slope profile number	L (metres)	ST (degrees)	number of gul.	ril.	cfl
1	371	2.7	0	0	0
2	273	2.8	0	0	0
3	417	3.6	0	0	0
4	331	4.6	0	1	0
5	662	5.5	0	0	0
6	864	3.2	0	0	0
7	408	5.0	0	0	0
8	539	3.7	0	0	0
9	545	4.4	0	0	0
10	594	4.2	0	0	0

(for key see Table 6.1)

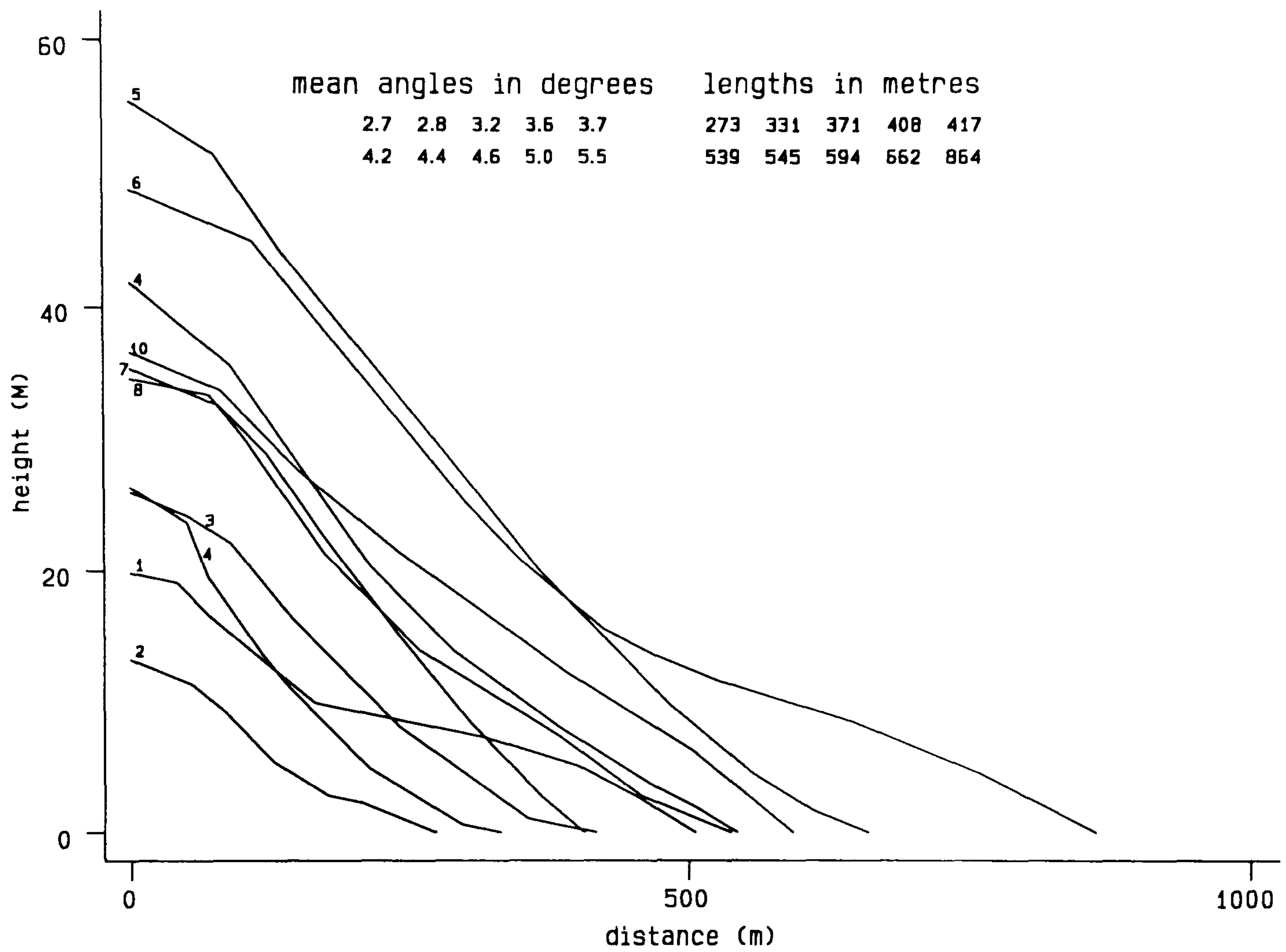


Figure 6.16 Gobba slope profiles

6.4.2 The relationship between soil properties and slope position

6.4.2.1 Soil texture

Like Magra, clay was the dominant type of texture at Gobba; out of the 30 soil samples analyzed for particle size distribution, 15 had clay, 7 silty clay loam and 5 had clay loam textures (Table 6.17). Relationships between slope position and soil texture are not strong. Generally, fine textured clayey soils were more frequent on upper slopes than lower and slightly coarser textured loams more frequent on lower slopes, the exact opposite of what might have been expected (Kleiss, 1970). This is may be related both to the relatively high per cent of vegetation cover and organic matter content that these upper slopes have, thus reducing runoff; and also to the fact that clay soils are resistant to erosion, hence only the relatively larger particles if any would be eroded. Overall, however, textures at all positions are relatively fine.

Table 6.17
Frequency of texture classes and means of soil properties, angles and percent of vegetation cover by slope position.

slope position	soil texture class. c	tc	cl	tcl	tl	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc (%)
lower	3	1	2	4	0	41.2	1.4	3.3	3.3	25.7
middle	7	1	0	2	0	55.8	1.0	3.2	3.7	21.8
upper	5	0	3	1	1	40.8	1.6	3.5	5.2	32.2
t/mean	15	2	5	7	1	45.9	1.4	3.3	4.0	26.6

(for key see Table 6.2)

6.4.2.2 Soil depth

Soils on the lower slopes were marginally deeper than those on the upper slopes. The deepest soils were however on the middle slopes, an unexpected finding (Figure 6.17a). A possible explanation is that any material eroded from the upper slopes is deposited on the very gentle middle slopes.

6.4.2.3 Organic matter

The organic matter content of all slope positions at Gobba was low, with an overall mean of 1.3%. In addition, this site has the lowest organic matter of the 6 sites, a fact reflecting the impact of cultivation on organic matter values. In addition, soil under cultivation has been shown to undergo some changes in its chemical and physical properties, including a decrease in organic matter, an increase in bulk density and a decrease in porosity (Bouma and Hole, 1971). The highest concentration was found on the upper slopes and the lowest was found on middle slopes (Figure 6.17b). The relatively high values of organic matter on upper slopes are attributed to the marginally higher frequency of fruit trees areas found on these positions. Fruit tree areas recorded the highest organic matter in this site. In contrast, middle slopes have the lowest organic matter as a result of the existence of the cleared areas.

6.4.2.4 Infiltration rate

It is known that shrinking cracks that develop during drying of a swelling clay soil increase the infiltration rate especially when these cracks are open to the surface (Ritchie et al., 1974). Although the infiltration rate was affected at most sites by the existence of cracks, at Gobba, the rates are relatively low; the highest was 3.5 cm hr^{-1} and the lowest was 3.2 cm hr^{-1}. This can be explained by the fact that as the soils wet and expand their porosity decreases and hence so does infiltration rate. In a

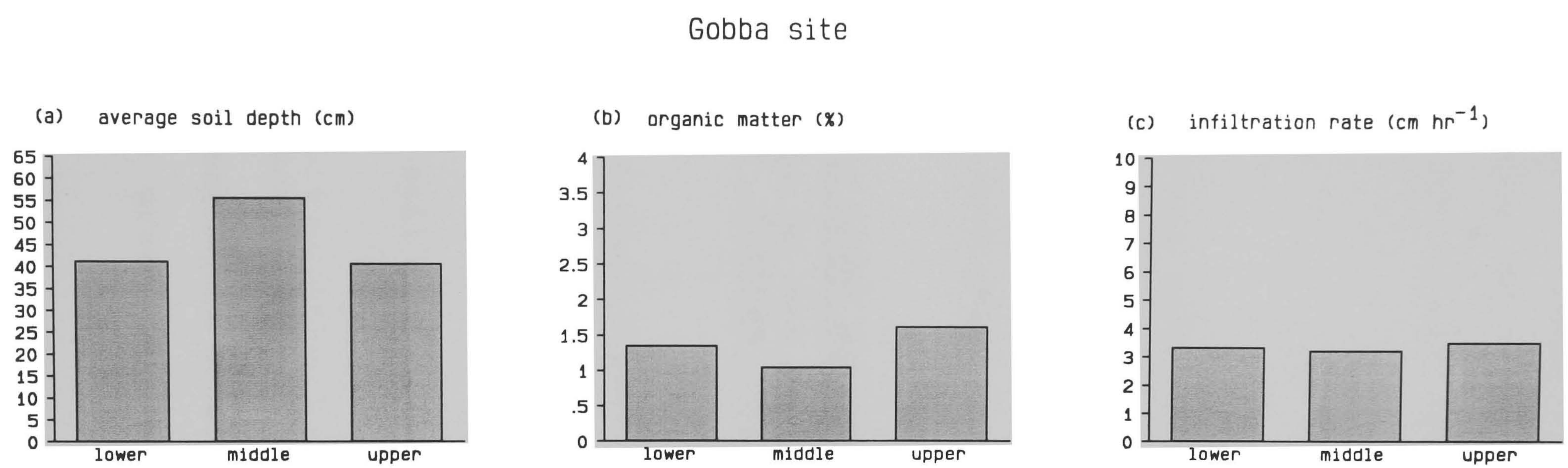


Figure 6.17 Mean soil properties by slope position

study of infiltration rate in vertisols in Puerto Rico, it was suggested that infiltration rates range between 0.18 cm hr^{-1} (min) and 9.58 cm hr^{-1} (max) (Lal, 1979b). Although, as Figure 6.17c shows, the rates of infiltration are broadly similar on all slope positions, the upper slopes recorded the marginally highest rates and middle slopes the lowest. This result again highlights the importance of organic matter.

6.4.2.5 Types of land use

The main types of land at Gobba were dry grass, wheat and barley, and fruit trees. Cleared land was encountered twice (Table 6.18). Whilst there was a total absence of natural vegetation four slope positions were under irrigated vegetables.

Table 6.18 Types of land use by slope position.

slope position	type of land use d/grass	w/barley	f/trees	vegetable	cleared
lower	3	5	1	1	0
middle	5	1	2	0	2
upper	2	2	3	3	0
total	10	8	6	4	2

(for key see Table 6.4)

6.4.3 The relationship between soil properties and land use

6.4.3.1 Soil texture

There was no clear relationship between land use and soil textures, with the highest concentration of both fine and coarse textures being related to dry grass and wheat/barley (Table 6.19).

Table 6.19 Frequency of texture classes and means of soil properties, angles and per cent cover by land use.

type of land use	soil text. classes c	tc	cl	tcl	tl	SD (cm)	OM (%)	IR cm hr^{-1}	pcc (%)
d/grass	5	1	1	2	1	49.4	1.2	2.7	24.0
w/barley	4	0	0	4	0	44.1	1.6	3.4	24.0
f/trees	2	1	2	1	0	31.0	1.6	3.5	29.5
vegetable	2	0	2	0	0	62.0	1.2	4.8	43.5
cleared	2	0	0	0	0	48.5	0.7	3.0	07.0
total	15	2	5	7	1	45.9	1.3	3.3	26.6

(for key see Tables 6.2 and 6.4)

6.4.3.2 Soil depth

The deepest soils of all 6 sites studied (mean 62 cm) were recorded at Gobba. Within the site, the deepest soils were under arable cultivation and the shallowest under fruit trees (Figure 6.18a).

6.4.3.3 Organic matter

Organic matter content of the soils of Gobba is everywhere very low, and on average is the lowest of all six sites (Figure 6.18b). The highest levels (1.6%) are found under wheat and barley and fruit trees; whilst the level under fruit trees is attributable to inputs from leaf fall etc., its generally low level may be due to the fact that soil between the trees is cultivated. The similar levels under wheat and barley are unusual, given the tendency for cultivation to reduce organic matter (see discussion in section 6.2.3.3). The relatively high organic matter must be due to wheat and barley residues incorporated into the soil and the manure added to the soil by animals grazed in these areas after harvesting.

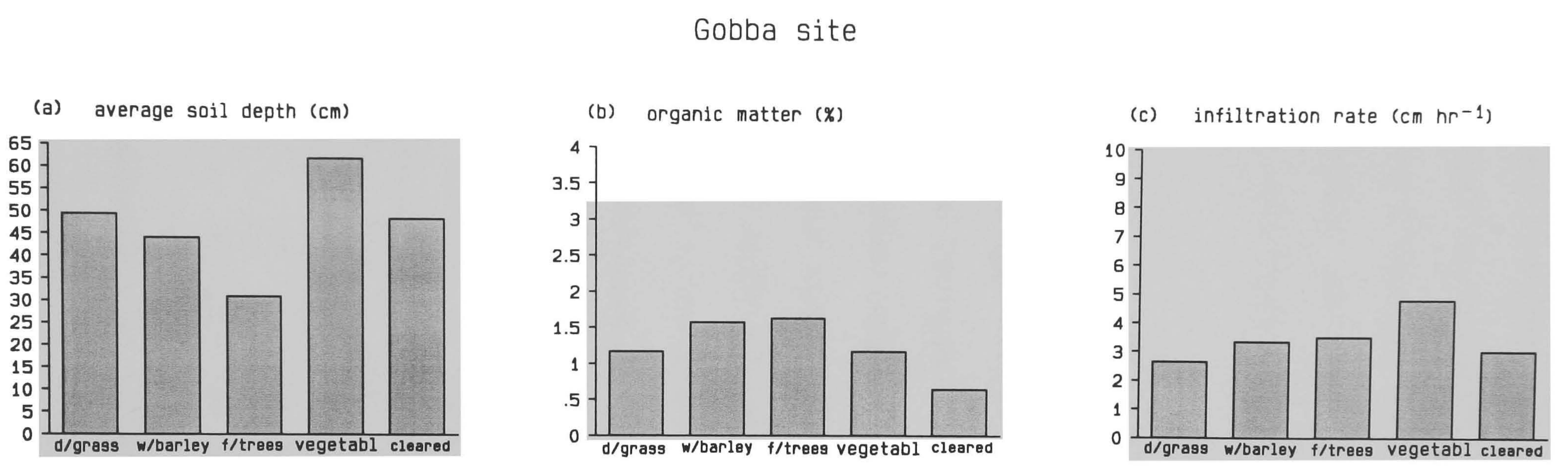


Figure 6.18 Mean soil properties by land use

6.4.3.4 Infiltration rate

The highest infiltration rate was found to be related to vegetables areas (Figure 6.18c). However, if we exclude vegetable and cleared land types of land use, which recorded the lowest organic matter in this site, infiltration rates for the rest of the land uses showed a significant influence by organic matter. Vegetable areas recorded high infiltration rates because of the continuous loosening of their soils during cultivation. In the case of cleared land, the high infiltration rate must be linked to the method of clearing.

6.4.3.5 Soil surface characteristics and erosion features

The main surface character of the soils of this site is cracking (Table 6.20). Cracks were recorded under all types of land use. However, areas of dry grass and cereals recorded the highest incidence of cracking in this site; these areas were also characterized by clay textures and high percent of bare ground. Apart from a small rill encountered in an area of fruit trees no other evidence of erosion was encountered at Gobba (Table 6.21).

Table 6.20 Frequencies of soil surface characteristics and percent of cross-profile covered by bare ground, stones and exposed outcrop by land use

type of land use	no. of c.p.	frequency of comp.	crack	%of c.p. covered by b/grd	stn	oce
d/grass	10	0	7	45.5	18.5	0
w/barley	8	0	7	53.8	16.9	0.6
f/trees	6	1	2	60.8	12.5	0
vegetable	4	0	3	48.8	12.5	0
cleared	2	0	2	97.5	2.5	0

(for key see Table 6.7)

Table 6.21 Frequencies of soil erosion features by land use.

frequency of	type of land use d/grass	w/barley	f/trees	vegetable	cleared
gullies	0	0	0	0	0
rills	0	0	1	0	0
cfl	0	0	0	0	0

(for key see Table 6.8)

6.5 Shahhat site

As with Gobba, two types of soils were found at the Shahhat site. These are vertic brown soils, which is the soil type of slopes 1, 2, and 3, and ferrosiallitic red soil, which is the soil type of slopes 4-10. Both soil types contain high amounts of clay and they exhibit cracking and become hard when dry and sticky when wet, especially the vertic brown. With such a contrast of soil types at Shahhat, where appropriate these divisions will be included in the cross tabulations.

6.5.1 Topographic relationships

As can be seen from Table 6.22, erosion occurs on both soil types. However, slopes of vertic brown soil were generally longer and gentler than those of the ferrosiallitic red soil (Figure 6.19a). Overall there is no clear relationship between frequency of erosion features and either slope angle or length on either soil (Figure 6.19b). Slope angles decrease from upper to middle positions then increase again on the lower positions; this latter increase is an anomaly caused by the two convex slopes 7 and 8. Excluding these two there is a general trend of decreasing slope angle downslope.

Table 6.22 Slope profile measurements and soil erosion features for each soil type.

soil type	slope no.	L metres	ST degrees	number of gul.	ril.	cfl
vertic brown	1	304	5.6	0	1	1
	2	439	8.8	1	0	0
	3	479	5.8	1	1	1
ferro-siallitic red	4	439	7.1	2	0	1
	5	319	7.1	1	0	0
	6	303	5.9	1	0	1
	7	461	16.4	0	0	0
	8	384	9.1	0	0	0
	9	409	7.5	0	1	1
	10	279	6.5	0	1	1

(for key see Table 6.1)

6.5.2 The relationship between soil properties and slope position

6.5.2.1 Soil texture

The texture classes of these soils show that both types, especially the vertic brown, had less fine textures than would be expected (Tables 6.23 and 6.24). Some 60% of the ferric red soil have textures of clay loam or finer, whilst only 30% of the vertic brown soils are clay loam or finer (GEFLI, 1975). In both cases the upper and middle slopes texture classes are finer than those of lower slopes. As with the slope position at Magra and Gobba, this pattern is the reverse of what was expected (see discussion in section 6.5.2.3 below).

Table 6.23
Frequency of texture classes and means of soil properties, angle and vegetation cover by slope position (the site).

slope position	texture classes c	tc	sc	cl	tcl	tl	l	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc (%)
lower	1	0	0	4	1	1	3	26.0	2.9	6.1	8.3	30.4
middle	1	0	0	7	1	0	1	22.3	2.6	6.9	7.8	32.4
upper	3	1	1	3	2	0	0	21.7	2.3	6.9	8.5	31.5
t/mean	5	1	1	14	4	1	4	23.4	2.6	6.7	8.2	31.4

(for key see Table 6.2)

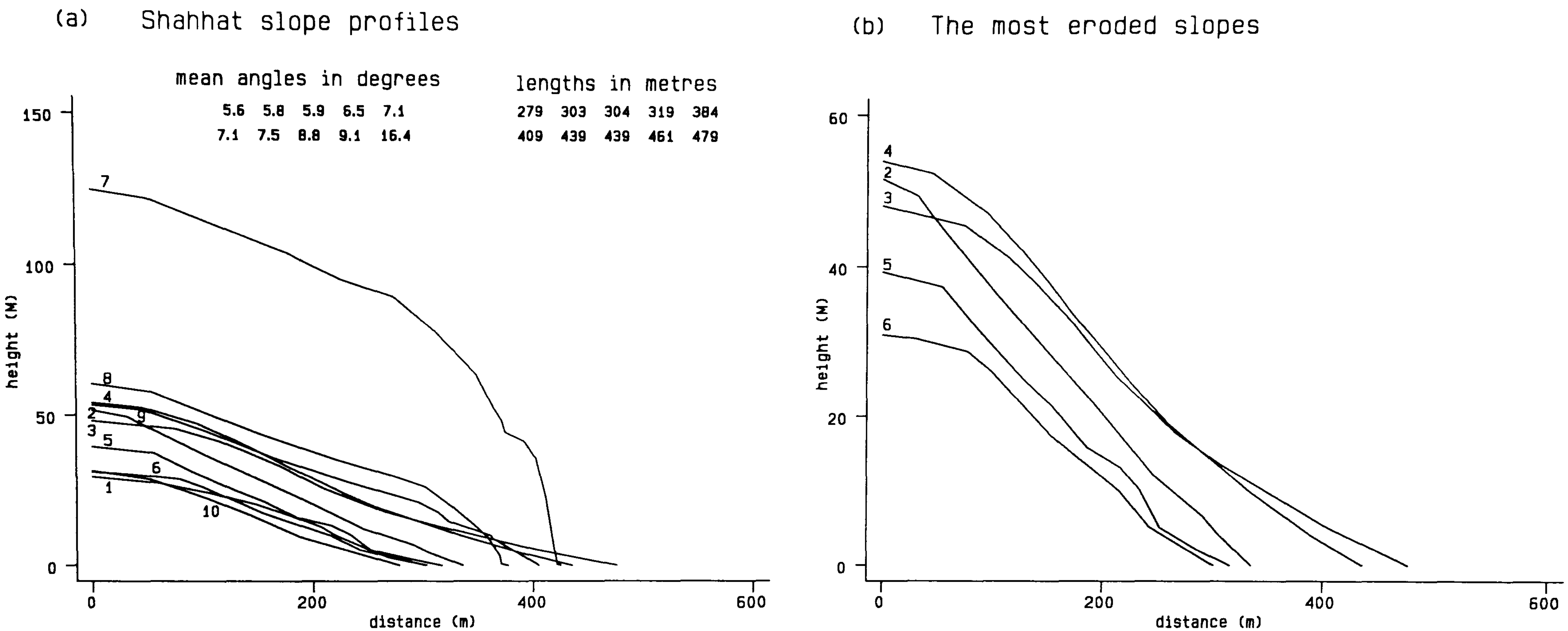

(a) Shahhat slope profiles
mean angles in degrees
5.6 5.8 5.9 6.5 7.1
7.1 7.5 8.8 9.1 16.4
lengths in metres
279 303 304 319 384
409 439 439 461 479
height (M)
distance (m)
(b) The most eroded slopes
height (M)
distance (m)

Figure 6.19

Table 6.24
Frequency of texture classes and means of soil properties, angle cover by slope position (the two soil types).

(a) vertic brown soil

slope posit.	c	tc	sc	cl	tcl	tl	l	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc (%)
lower	0	0	0	0	0	1	2	23.5	2.5	3.8	6.0	31.3
middle	0	0	0	2	0	0	1	18.1	2.1	7.2	8.8	26.7
upper	1	0	0	0	2	0	0	21.2	2.2	8.0	9.3	30.3
t/mean	1	0	0	2	2	1	3	21.0	2.3	6.3	8.1	29.4

(b) ferric red soil

slope posit.	c	tc	sc	cl	tcl	tl	l	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc (%)
lower	1	0	0	4	1	0	1	27.1	2.9	7.5	9.3	30.0
middle	1	0	0	5	1	0	0	24.1	2.8	6.7	7.3	34.9
upper	2	1	1	3	0	0	0	21.9	2.5	6.4	8.1	32.0
t/mean	4	1	1	12	2	0	1	24.4	2.7	6.8	8.2	32.3

6.5.2.2 Soil depth

From Figure 6.20a, it is clear that the ferric soil is generally deeper than vertic brown, the mean soil depths being 24.4 cm and 21.0 cm respectively. Both soils however show similar depth distributions with slope positions, in that depth increases downslope.

6.5.2.3 Organic matter

Mean of organic matter for the ferric red soil is 2.7% and 2.3% for the vertic brown. Both soils and the site showed an increase in organic matter downslope (Figure 6.20b).

As mentioned earlier, soil depth and organic matter were expected to increase downslope. However, in the case of both soils, especially the vertic brown, the low values of organic matter on the upper slopes are directly related to the active erosion as a result of the increased angle of gradient of this

Shahhat site

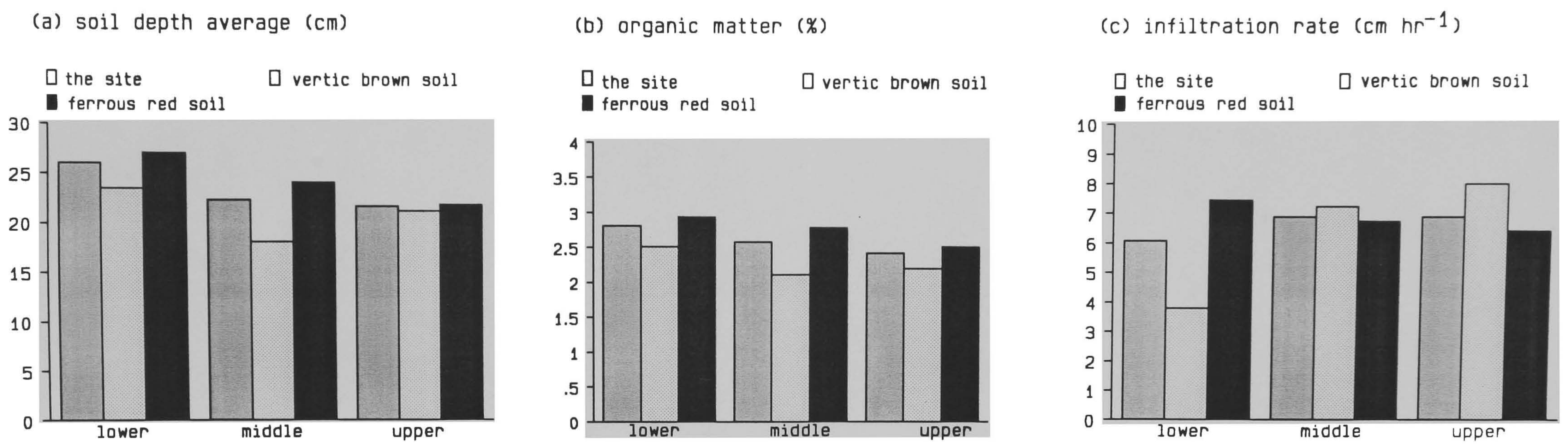


Figure 6.20 Mean soil properties for the site, vertic brown and ferrous red soils by slope position

position (Furley, 1971 and Whitfield and Furley, 1971). In contrast, lower slopes, in addition to their gentle angles, are areas of grass and residue cover, which helped to reduce sediment loss, and the result was a general increase in organic matter and soil depth. For the same reason, fine soils were expected to have the same trend as organic matter and soil depth, i.e. increases downslope. Interestingly, the opposite was the case with more fine textures on the upper than on the lower slopes. The only explanation is that these upper slopes, due to their steep angles, are so affected by erosion that they have lost all their topsoils and what they have now is the exposed subsoils, which contain greater amount of clay and less amount of organic matter (Afyuni, et al., 1993; Olson and Beavers, 1987; Pierson and Mulla, 1990).

6.5.2.4 Infiltration rate

The mean rate of infiltration, at this site, is 6.7 cm hr^{-1} for the site, 6.8 cm hr^{-1} for the ferric red and 6.3 cm hr^{-1} for the vertic brown soil. As Figure 6.20c shows, whilst the overall mean rates decrease downslope, this pattern is only true for the vertic brown soil. The ferric red soil shows a progressive increase in rate downslope. This latter is associated with an increase in organic matter content and depth of soil downslope and a coarsening in texture. Table 6.24 shows an identical trend in the soil properties of the vertic brown soil yet infiltration rate decreases downslope. In the absence of a soil crust the only explanation can be an increase in compaction and bulk density as a result of cultivation.

6.5.2.5 Soil erosion features

On both soil types, all the recorded gullies and most of the rills and concentrated flows were found on lower slopes. Upper slopes were free of these features (Table 6.25).

Table 6.25 Distribution of erosion features by slope position.

slope position	vertic brown			ferric red		
	gul.	ril.	cfl	gul.	ril.	cfl
lower	2	1	1	4	2	3
middle	0	1	1	0	0	1
upper	0	0	0	0	0	0

(for key see Table 6.1)

6.5.2.6 Land use and slope position

Like the Gobba site, no natural vegetation was recorded on any of the 10 slopes at Shahhat. However, at Shahhat, land use types are restricted to dry grass, wheat and barley and fruit trees. Fruit trees are the dominant type being recorded 17 times (Plate 6.6). They dominate land use on the upper and middle slopes of both soil types, whilst dry grass and wheat and barley dominate the lower slopes (Tables 6.26 and 6.27).

Table 6.26 Types of land use by slope position (the site).

slope position	type of land use		
	d/grass	w/barley	f/trees
lower	4	4	2
middle	2	1	7
upper	0	0	10
total	6	5	19

Plate 6.6
Fruit cultivation is the dominant type of land use at Shahhat site. A farm of apple trees located on upper slope; these trees are generally characterized by their small size.

Table 6.27 Types of land use by slope position (the two soils).

soil type	slope position	type of land use d/grass	w/barley	f/trees
vertic brown	lower	1	1	1
	middle	1	0	2
	upper	0	0	3
	total	2	1	6
ferrosial-litic red	lower	3	3	1
	middle	1	1	5
	upper	0	0	7
	total	4	4	13

(for key see Table 6.4)

6.5.3 The relationship between soil properties and land use

6.5.3.1 Soil texture

The clay textured upper and middle slopes of both soil types were mainly used for fruit trees, whilst the slightly coarser textured lower slopes were used for cereal cultivation (Tables 6.28 and 6.29).

6.5.3.2 Soil depth

The land use and soil depth relationships are more complex. On the vertic brown soils wheat and barley are associated with the deepest soils and fruit trees the shallowest. On the ferric red soils, however, dry grass and wheat and barley were found on the deepest and shallowest soils respectively (Figure 6.21a).

6.5.3.3 Organic matter

In the site and in both soil types, the highest organic matter is related to wheat and barley, and the lowest to dry grass land use (Figure 6.21b).

Table 6.28 Frequencies and means of soil properties by land use (the site).

type of land use	c	tc	sc	cl	tcl	tl	l	SD (cm)	OM (%)	IR (cm/hr^{-1})	pcc (%)
	texture classes										
d/grass	1	0	0	2	0	0	1	24.3	2.1	5.9	26.6
w/barley	0	0	0	3	0	0	2	22.9	3.3	7.3	32.8
f/trees	4	1	1	9	4	1	1	23.2	2.6	6.7	32.9
t/mean	5	1	1	14	4	1	4	23.4	2.6	6.7	31.4

Table 6.29 Frequencies and means of soil properties by land use (the two soils).

soil type	type of land use	c	tc	sc	cl	tcl	tl	l	SD cm	OM %	IR cm hr^{-1}	pcc (%)
		texture classes										
v. brown	d/grass	0	0	0	1	0	0	1	21.1	2.2	5.0	28.5
	w/barley	0	0	0	0	0	0	1	26.2	3.4	4.2	32.0
	f/trees	1	0	0	1	2	1	1	20.0	2.1	7.2	29.3
	t/mean	1	0	0	2	2	1	3	21.0	2.3	6.3	29.4
ferr. red	d/grass	1	0	0	2	1	0	0	25.8	2.0	6.5	25.8
	w/barley	0	0	0	3	0	0	1	22.1	3.2	8.4	33.0
	f/trees	3	1	1	7	1	0	0	24.6	2.8	6.5	34.6
	t/mean	4	1	1	12	2	0	1	24.4	2.7	6.8	32.3

(for key see Table 6.2)

6.5.3.4 Infiltration rate

Again the pattern of infiltration rates with land use is complex and contradictory (Figure 6.21c). The ferric red soils have the highest infiltration rates and these are associated with wheat and barley and relatively high organic matter. Vertic brown soil maximum infiltration rates are associated with fruit trees and the lowest organic matter content.

6.5.3.5 Soil surface characteristics and erosion features

In both the site and the two soils, all the gullies and most of the other features were recorded in dry grass and wheat and barley areas (Tables 6.30, 6.31, 6.32 and 6.33).

Shahhat site

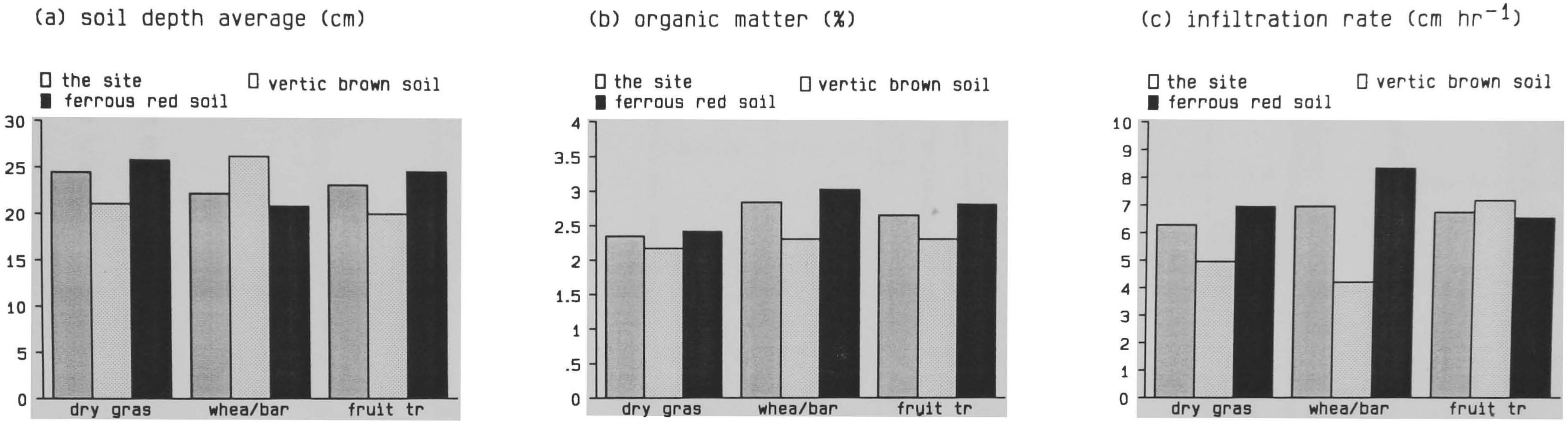


Figure 6.21 Mean soil properties for the site, vertic brown and red soils by land use

Table 6.30 Frequencies of soil surface characteristics and percent of cross-profile covered by bare ground, stones and exposed outcrop according to land use (the site).

type of land use	no. of c.p.	frequency of comp.	crack	%of c.p. covered by b/grd	stn	oce
d/grass	7	1	1	62.9	16.4	0
w/barley	4	1	1	56.3	16.3	5
f/trees	19	1	6	59	14.7	7.5

(for key see Table 6.7)

Table 6.31 Frequency of erosion features by land use (the site)

type of land use	frequency of gul.	ril.	cfl
d/grass	4	2	2
w/barley	2	0	1
f/trees	0	2	3

Table 6.32 Frequencies of soil surface characteristics and percent of cross-profile covered by bare ground, stones and exposed outcrop by land use type (the two soils).

soil type	type of land use	no. of c.p.	frequency of comp.	crack	%of c.p. covered by b/grd	stn	oce
v. brown	d/grass	2	0	1	60	15	0
	w/barley	1	1	1	70	15	0
	f/trees	6	1	3	84.2	4.2	0
ferr. red	d/grass	5	1	0	53	17	0
	w/barley	3	0	0	51.7	16.7	6.7
	f/trees	13	0	3	53.5	19.6	2.3

(for key see Table 6.7)

Table 6.33 Distribution of soil erosion features by land use.

type of land use	vertic brown gul.	ril.	cfl	ferrous red gul.	ril.	cfl
d/grass	1	1	1	2	1	1
w/barley	1	0	0	2	0	1
f/trees	0	1	1	0	1	2

(for key see Table 6.8)

6.6 Conclusion

This chapter has presented a detailed cross tabulation analysis of erosion occurrence with various soil, vegetation/land use and slope characteristics. From the preceding discussion it is clearly evident that not all six sites studied show the same complex interacting relationships between the various factors.

At Lussaita, Bayyada, Batta and Shahat the steeper upper slopes were either not cultivated or used for fruit growing, whilst the middle and lower slopes were invariably cultivated for cereals. At Magra the steeper slopes were similarly uncultivated, but in this instance the uncultivated areas were located on the middle and lower slopes, with cultivation being found on the more gentler sloping upper slopes. The Gobba site, which is characterised by more open, gentler slopes had no uncultivated areas.

Erosion features were recorded at all sites except the shallow sloped Gobba site. In the five remaining areas rill and gully features were common, with the exception of the Magra site, these features were confined to middle and lower slopes. At Magra with its different topography, erosion features were confined to the upper and middle slopes. The common feature at all five site exhibiting erosion features was that these were invariably associated with ares of cultivation.

Of the four sites that had similar topographic and land use characteristics, Shahhat had a further variation in having two distinct soil types. Nevertheless, the soil catena at all four sites showed a standard trend of increasing soil depth down slope. Other characteristics however were not uniformly repeated in all areas. At Lussaita, Bayyada and Batta, organic matter content and infiltration rates decreased down slope and textures became finer. The more complex soil pattern at Shahhat showed both similarities and differences to these trends; on the vertic brown soils, organic matter content increased down slope, whilst infiltration rate decreased and the surface soil texture became coarser down slope. The fersiallitic red soils showed a similar coarsening of texture down slope, but both organic matter content and infiltration rates increased down slope.

When comparison is made between land use and incidence of erosion, a constant relationship is apparent between increased incidence of erosion and cereal cultivation. There is a less clear relationship between incidence of erosion and soil properties, for example organic matter content and infiltration rate. Nevertheless the general pattern is for reduced organic matter content and infiltration rates to be associated with increased frequency of erosion.

Thus whilst certain trends in the distribution of erosion features can be associated with slope characteristics, certain soil properties and land use, it is by no means consistent. The complex interaction of these different factors together with rainfall is examined in Chapter 8.

Chapter 7

Soil loss measurements

7.1 Introduction

Soil erosion measurement had the aim of assessing the monthly rate of soil removal from each slope plot during the rainy season of 1992-93. These slopes were monitored over six months from November 1992 to April 1993. The measurements were on a monthly basis, in which a reading was taken at the end of each month. The first reading, at the end of November, was taken by measuring the distance between the pin head and the washer - 2.5 cm (the exposed part of the pin). The rest of the readings were calculated as the measured distance between the pin head and the washer - 2.5 cm + the previous reading.

There are several reasons why Al-Kouf National Park was selected as the location for the installation of erosion pins rather than any of the other sites:

1. The site has a rain-gauging station.
2. It is representative of the main vegetation and land use types in the study area; natural vegetation with some wheat and barley cultivation.
3. It has a variety of slopes with different angles and aspects.
4. The chosen site was located between the administration building and the rain-gauging station and surrounded by barbed-wire fencing. Therefore, the pin site was watched daily by the employees.
5. The site was readily accessible.

As explained in Chapter 4, four slopes were selected for the installation of pins. These slopes had different angles; two were gentle slopes and two were relatively steep. Also they had different land use types, as two were cultivated slopes and two had natural vegetation cover (Table 7.1 and Figure 7.1). However, there was some variation in the natural vegetation; slope 2 comprised trees, shrubs, and grass, while slope 4 was dominantly shrubs. This cover was relatively continuous on slope 2 and formed a good protection for the soil. In contrast, on slope 4 the vegetation was less continuous with some patches of bare ground. Slopes 1 and 3 were cultivated with wheat and barley and they were partially covered with straw.

Table 7.1 Slope profile measurements and type of land use.

slope profile	L metres	ST degrees	type of land use nat.vegn	w/barley
1	74	3.1	0	1
2	54	2.0	1	0
3	64	4.5	0	1
4	54	5.0	1	0

L=length. ST=steepness. nat.vegn=natural vegetation.
w/barley=wheat and barley.

7.2 Site properties

7.2.1 Soil properties and slope position

Clay is clearly the dominant textural class at Al-Kouf, with 9 of the 12 samples having such a texture (Table 7.2). Clay soils are evenly distributed according to slope position: i.e. 3 were found on lower, 3 on middle and 3 on upper slopes. Overall there was a slight tendency for texture to become finer downslope.

The mean organic matter content at 3.1% was the same for all

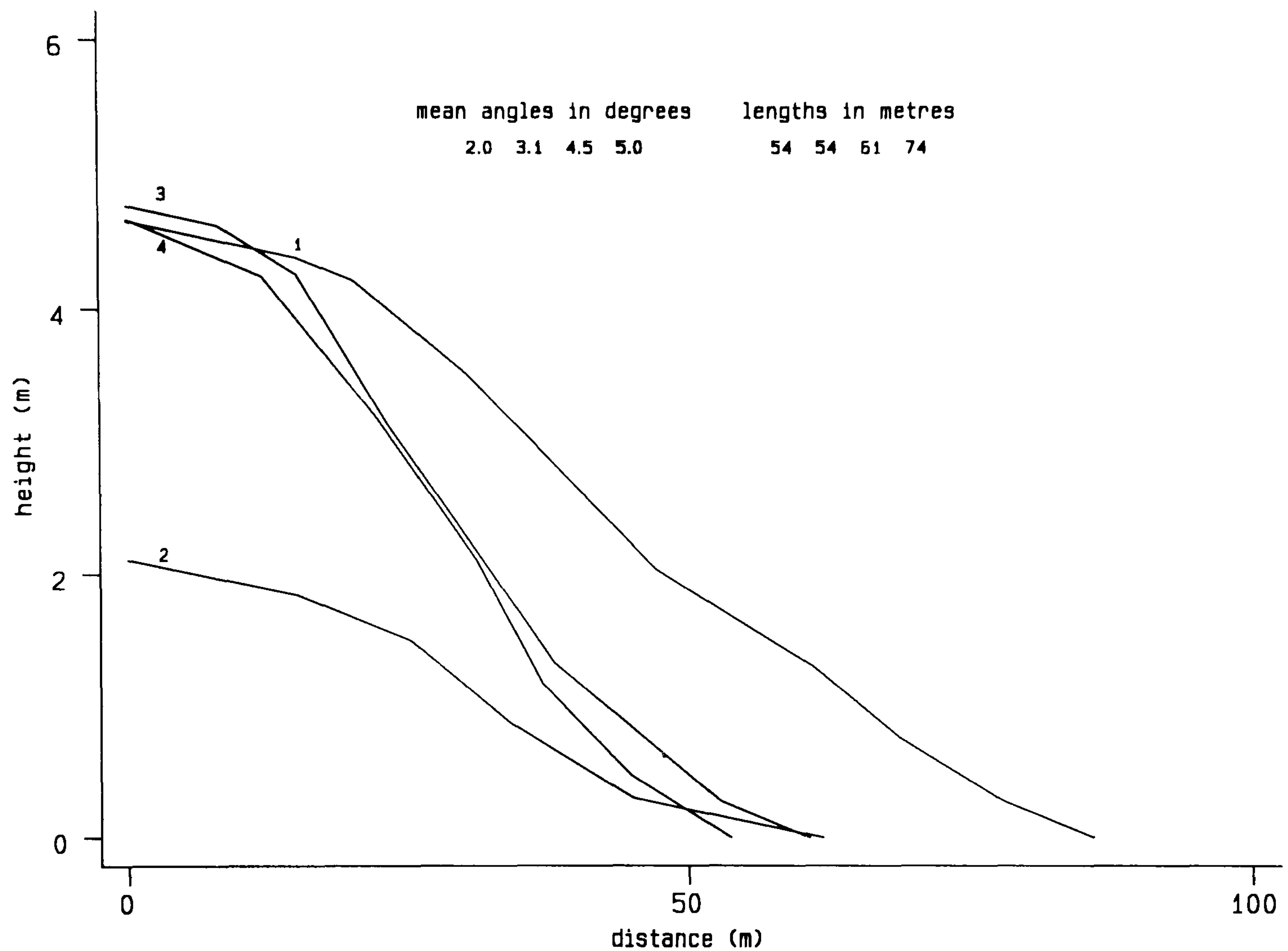


Figure 7.1 Al-Kouf slope profiles

slope positions. Both soil depth and infiltration rate however increased downslope (Figures 7.2a, b and c).

Table 7.2
Frequency of texture classes and means of soil properties, angles and per cent of vegetation cover by slope position.

slope posit.	texture class c	cl	tl	l	SD (cm)	OM (%)	IR cm hr^{-1}	angle degr.	pcc (%)
lower	3	1	0	0	63.8	3.1	10.5	2.3	42.5
middle	3	0	1	0	50.0	3.1	10.0	3.8	37.5
upper	3	0	0	1	45.0	3.1	9.3	4.3	32.5
t/mean	9	1	1	1	52.9	3.1	9.9	3.4	37.5

c=clay cl=clay loam tl=silt loam l=loam
SD=soil depth OM=organic matter IR=infiltration rate
pcc=percent of vegetation cover.

7.2.2 Soil properties and land use

The main texture class at this site, clay, was recorded 5 times under natural vegetation and 4 times in cultivated areas. Although this difference is slight, it gives an indication that cultivated areas might be losing more fine material than natural vegetation areas. Organic matter content is the same for both types of land use. This can be attributed to a similar input of plant residues. Soils of cultivated areas are deeper than those of natural vegetation. Infiltration rates, however, are higher under natural vegetation than cultivated, this despite the soil being less deep and having the same organic matter content as that of cultivated areas (Figures 7.3a, b and c). This can be explained by the greater incidence of cracking under the natural vegetation than in the cultivated areas. A second possibility is the reduction in structural stability and hence porosity as a result of cultivation at the cultivated areas.

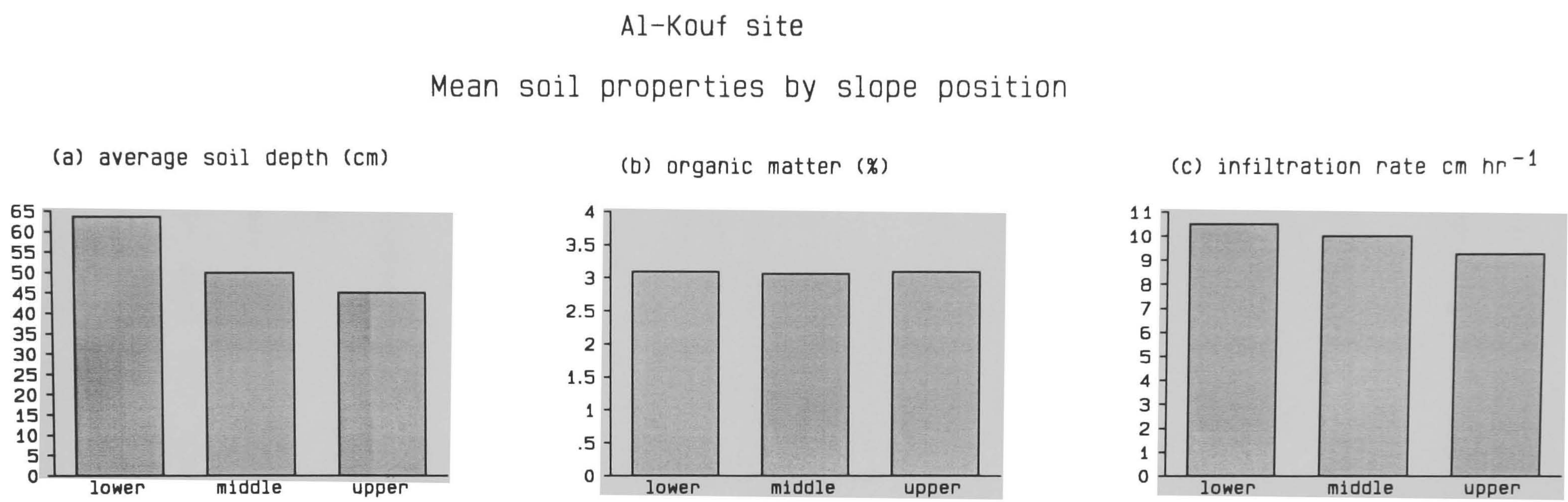


Figure 7.2 Variations of soil properties related to slope position.

Table 7.3 Frequency of texture classes and means of soil properties and per cent cover by land use.

type of land use	texture class c	cl	tl	l	SD (cm)	OM (%)	IR cm hr^{-1}	pcc (%)
nat.vegn	5	1	0	0	43.3	3.1	10.0	49.2
w/barley	4	0	1	1	62.5	3.1	9.8	25.8
t/mean	9	1	1	1	52.9	3.1	9.9	37.5

(for key see tables 7.1 and 7.2)

7.2.3 Soil surface characteristics

The most characteristic surface feature of these clay soils was severe cracking, which was recorded on each slope position. There were more cracks under natural vegetation than under arable areas because cultivation of the latter caused the cracks to be partially infilled. Interestingly crusting was absent at both cultivated and naturally vegetated areas (Table 7.4).

Table 7.4 Frequency of soil surface characteristics and type and per cent cover of cross profiles by land use.

type of land use	number of c.p.	s. character. cracks	% of c.p. covered by b/grd	stn	oce
nat.vegn	6	6	20.8	16.6	0.8
w/barley	6	5	39.2	25.8	0

c.p.=cross profile. b/grd=bare ground. stn=stones. oce=outcrop exposure.

7.3 Amount of soil removed and topography

7.3.1 Slope steepness and length

Although the difference between the angles of these slopes is fairly small (the steepest is 5° and the gentlest is 2°), the variation in soil loss rates for these slopes is substantial (Table 7.5). These differences can be seen by comparing slopes 1 and 3 which differ in steepness, but have the same land use.

Al-Kouf site
Mean soil properties by land use

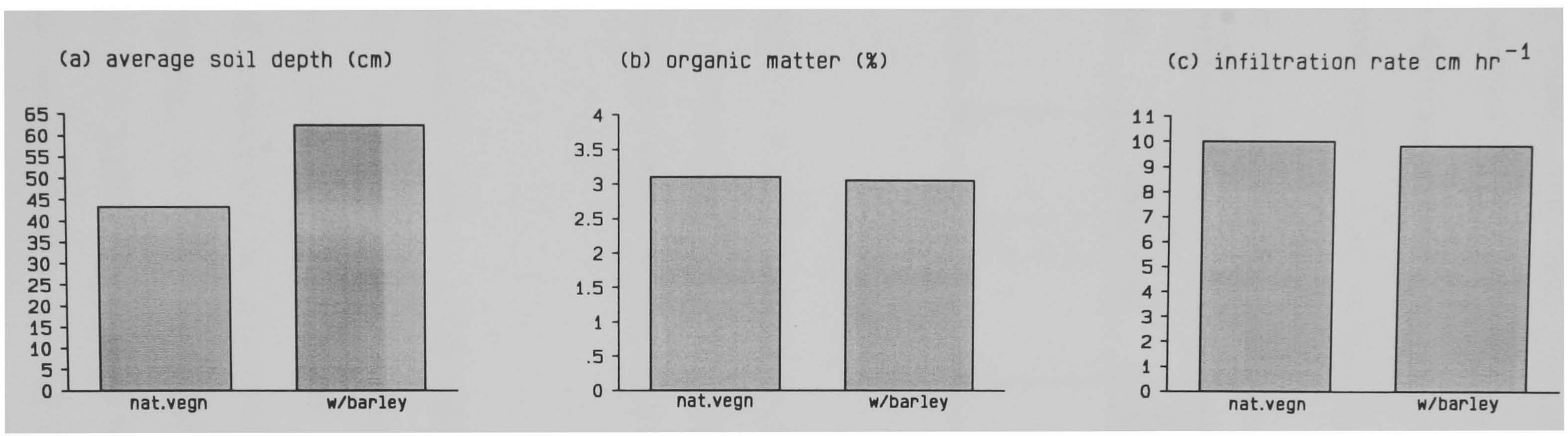


Figure 7.3 Variations of soil properties related to land use.

The amount of soil removed from slope 3 is much higher than that removed from slope 1, even though the latter is longer than the former. Apparently, the reason behind this is steepness, as slope 3 is steeper than slope 1. Also, the same result can be seen when comparing slopes 2 and 4, since both slopes have similar land use and length, but they have different steepness. Slope 4, which is the steepest, has lost more soil than slope 2.

Table 7.5 Average amount of soil removed as related to slope length and steepness.

slope no.	L metres	ST degrees	average depth of soil removed (mm)
slope 1	74	3.1	19.0
slope 2	54	2.0	9.9
slope 3	64	4.5	24.3
slope 4	54	5.0	15.6

(for key see table 7.1)

7.3.2 Slope position

As can be seen from Table 7.2 and Figure 7.2, there is little difference in either soil texture or organic matter between the three slope positions. However, soil depth and infiltration rate increase downslope.

From Table 7.6, it appears that, although all three slope positions have recorded soil removal, upper slope areas suffered greater erosion than lower slopes. The loss of soil from the lower slopes was partially replaced by accumulation from above. These average figures, however, conceal considerable variations. Some slopes, like slope 2, in fact show substantial deposition on their lower parts. This is probably a result of the combined effect of low angle and a good vegetation cover, as both can reduce runoff velocity and trap material removed from upper parts. However, some pins located on upper and middle slopes have also recorded accumulation of soil instead of removal. This is probably due to local small-scale variation in topography and density of vegetation cover.

Table 7.6 Average amount of soil removed by slope position.

position of slope	lower	middle	upper
amount of soil removed (mm)	8.7	19.4	24.0

7.4 Amount of soil loss and land use

Land use appears to be a very important factor that affects the slope runoff and sediment removal. The importance of this factor for the control of runoff and the removal of soil material can be shown by comparing the amount of soil removed from cultivated slopes and those of natural vegetation (Table 7.7). Ploughed soils were exposed to direct rainfall for the period at the beginning of the wet season before they were protected by crop cover. The importance of this lack of vegetation cover early in the wet season at the cultivated areas can be seen when two slopes, 3 and 4, of almost the same steepness but of different land use, are compared (see Table 7.5). The total amount of soil removed from slope 3 is more than 1.5 times that removed from slope 4. The importance of this reduced vegetation cover on cultivated areas, increasing overland flow and erosion, is emphasised by comparing slope 1 and slope 4. Although slope 4 is steeper than slope 1, the amount of soil removed from the latter is higher than that removed from the former. In addition, the small difference of the soil loss rates between the naturally vegetated upper slopes, areas of active erosion, and those of the cultivated lower slopes, where deposition is active, is further evidence of the importance of land use and vegetation cover in controlling erosion at this site (Table 7.7).

Table 7.7 Average amount of soil removed from each slope position by land use.

type of land use	average soil removed (mm) lower	middle	upper	total average (mm)
nat.vegn	5	15	19	13
w/barley	12	24	29	22

(for key see Table 7.1)

The difference in extent of erosion is not simply restricted to cultivated and non-cultivated slopes. There is also a difference between the naturally vegetated slopes. Although slope 2 is less steep than slope 4, there is also a difference in vegetation cover, slope 2 having a continuous cover of grass whilst slope 4 cover is variable, being a mixture of shrubs and areas of bare ground. This patchy vegetation cover encourages the concentration of runoff between the shrubs, resulting in an increased amount of soil removed from slope 4.

The importance of slope angle in influencing erosion can be seen by comparing slopes 1 and 3, having the same land use; assuming that other factors are constant, the difference in the amount of soil removed from each slope will reflect the different angles. As can be seen from Table 7.5 the steeper slope (3) has a greater soil loss than the less steep slope 1.

Concealed within this difference in 6 months total loss between slopes 1 and 3 are some interesting temporal variations (see Table 7.8). The greatest difference in rates of soil loss between the two slopes was when they were effectively bare ground. However, this difference was reduced toward the end of the season. This can be attributed to the gradual development of sufficient vegetation cover on the two slopes which, in turn, reduced the amount of soil loss in general and modified the effect of steepness by reducing the difference of soil loss between the two slopes.

Table 7.8 Monthly differences in rates of soil loss between slopes 1 and 3.

slope no.	average soil removed (mm) Nov.92	Dec.92	Jan.93	Feb.93	Mar.93	Apr.93
slope 1	4.9	2.8	4.0	3.1	2.6	2.0
slope 3	6.1	4.6	5.1	3.3	2.9	2.3

In conclusion, it appears that slope steepness, slope position, land use and vegetation cover are very important factors in soil erosion by water in this site. The effects of each factor are clear when treated separately, but these effects are further increased when these factors are combined. In addition, the effect of each factor appears to be largely influenced by land use and vegetation cover. For instance, slope 2 combined a small angle and good vegetation cover; thus, the amount of soil removed was very small. Other factors, like soil properties, especially texture and organic matter, appear to be of little importance since they vary little between the four slopes. In addition, the downslope increase of soil depth is a result of erosional and depositional processes along the slopes.

However, some lower slopes show an efficient removal of soil material, which was mainly attributed to land use.

7.5 Amount of soil loss and rainfall

7.5.1 Rainfall at Al-Kouf site

The average annual rainfall for the 12 year record at the Kouf station at 451 m a.s.l. and at 17.5 km distance from the coast was 400.6 mm. However, the 1992-93 total was only 254.1 mm, a quantity much lower than the average; 89.8% of the total rain fell in the months November to February, with 36.7% of the whole falling in January 1993.

The results of the erosion pin study discussed in this section represent the effect of only one wet season, which in comparison with the mean rainfall figures was drier than average. Further monitoring of the sites over a number of years is therefore necessary in order to establish an accurate assessment of soil loss in this area. One possible alternative either to the establishment of a long term monitoring site, or certainly as a support to it, is to examine the sedimentary sequence found in valley fills or accumulated behind the many Roman check dams in the area (Vita-Finzi, 1969). Such accumulation of sediment can often be dated using photo/thermoluminescent techniques or radiocarbon assay; more recent sedimentary deposition can be dated using Cesium^{-137} (Bell, 1982 and Mitchell et al., 1980). In some instances archaeological artifacts can be used. Thus by examining valley fill sediments it might be possible to place the current phase of erosion in an historical context and enable comparisons to be made between current and historic rates of erosion.

7.5.2 Amount of soil removed and monthly rainfall

As Table 7.9 and Figure 7.4 show, in November, the first month of the rainy season, although the soil was dry and cracked and infiltration rates are assumed to have been high (Chisci and Zanchi, 1981; De Meester and Eppink, 1980), there was a large amount of soil loss. This was in response to the amount of loose soil particles available to be removed and the absence of vegetation cover; during this time the soils, especially in cultivated areas, were almost bare. Without vegetation, much of the runoff energy is directed to soil erosion and to the removal of the detached material (Lopez and Romero, 1989). In December, a lower soil loss was recorded, due to a combination of lower rainfall and to the increasing grass cover on the naturally vegetated slopes. In January, although this was the wettest month, soil loss was quantitatively less than in November and proportionally less than December. This was probably due to the fact that much of the susceptible soil material was removed during the previous months and the crop cover protected the surface more efficiently, and the result was less soil loss.

In general, the amount of soil removed decreased toward the end of the season because of the general decrease of rainfall, coupled with increasing vegetation cover and increasing temperature, which in turn increased evaporation and hence loss of water from the surface. This is clear when the percent of the

Table 7.9 Monthly variations of rain and average soil loss in each month and according to land use.

month & year	rain (mm)	% of t. rain	aver.soil loss mm nv	w/b	total	% of t. loss nv	w/b	total
Nov.92	57.2	22.5	1.6	2.7	4.3	9.2	15.6	24.9
Dec.92	30.6	12.1	1.2	1.9	3.1	6.9	11.0	17.9
Jan.93	93.1	36.6	1.4	2.2	3.6	8.1	12.7	20.8
Feb.93	47.3	18.6	1.0	1.6	2.6	5.8	9.2	15.0
Mar.93	18.1	7.1	.7	1.4	2.1	4.1	8.1	12.1
Apr.93	7.8	3.1	.5	1.1	1.6	2.9	6.4	9.3
total	254.1	100	6.4	10.9	17.3	37	63	100

nv=natural vegetation w/b=wheat and barley

total rain and the percent of eroded soil for each month are compared. The overall results show that 42.8% of soil loss was removed in the beginning of the rainy season (November and December) although these two months received only 34.5% of the total rain of the season.

7.6 Soil pin erosion and deposition patterns

Figures 7.5, 7.6, 7.7, 7.8 and 7.9 show the patterns of soil loss and deposition on each slope, both temporal and spatial patterns, which were derived from the pin data (Table 7.10).

Table 7.10 Mean monthly removal and deposition of soil material on each slope (mm).

month	slope 1 R.	D.	slope 2 R.	D.	slope 3 R.	D.	slope 4 R.	D.	average R.	D.
Nov.	17.7	.2	9.6	.3	21.9	-	13.2	-	15.6	0.13
Dec.	10.2	-	7.2	.3	16.3	-	11.1	-	11.2	0.08
Jan.	4.5	.1	8.1	.7	17.8	-	11	.1	13.0	0.23
Feb.	11.6	.4	7	2.2	12.1	.2	9.7	.3	10.1	0.78
Mar.	9.9	.4	5.8	2.2	11.2	.7	7.6	.5	8.6	0.95
Apr.	8.1	.8	3.4	.6	8.9	.5	5.3	1.0	6.4	0.73
Total	72.0	1.9	41.1	6.3	88.2	1.4	57.9	1.9	64.9	4.32

R.=removal D.=deposition

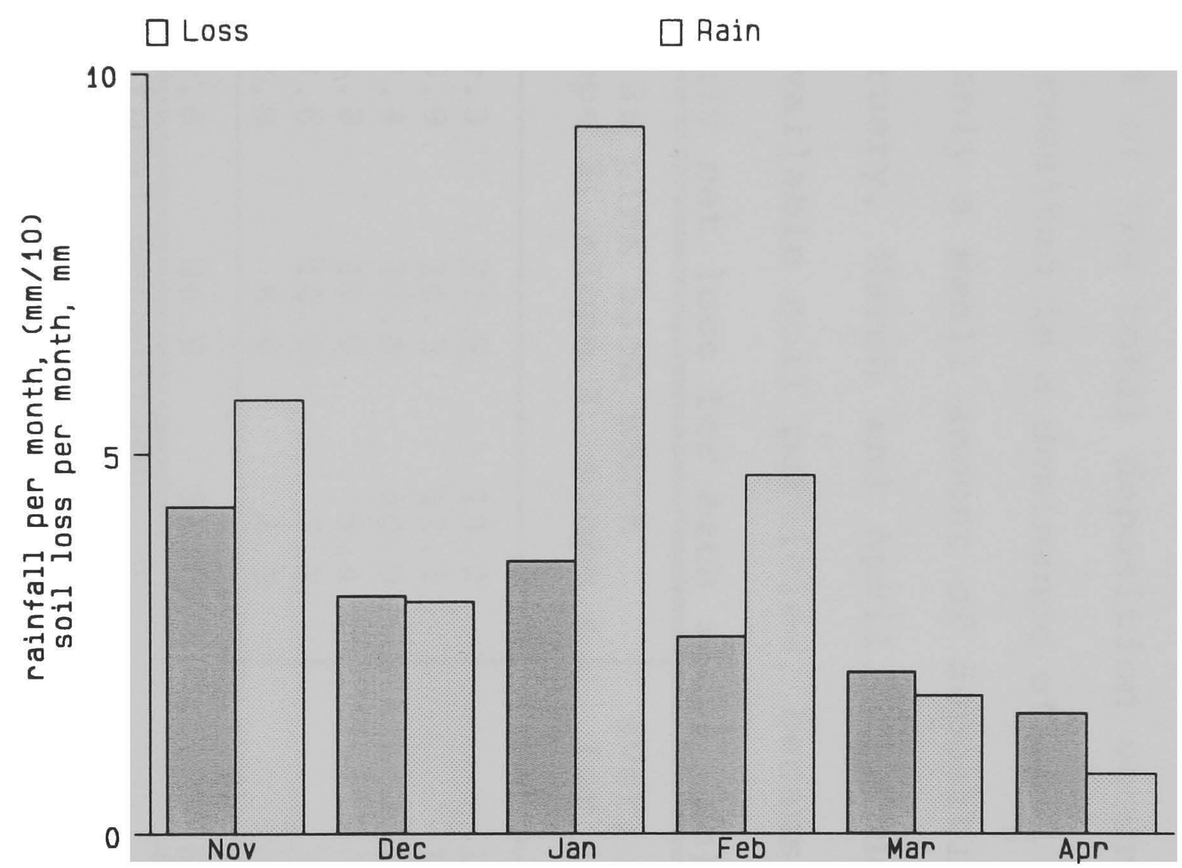


Figure 7.4 Rainfall and soil loss, November to April.

7.6.1 Temporal patterns

Temporal patterns, both monthly and seasonal for the four slopes, show a general decrease in soil loss and increase in deposition toward the end of the rainy season (Tables 7.10 and 7.11). This is in response to the lower cover of vegetation, the higher amount of available soil particles and the higher amount of rainfall (62.4% of the total) that characterised the first half of the rainy season, November, December and January. Consequently, during this half 61.1% of the total loss occurred; by contrast only 14.9% of the total deposition occurred (Table 7.13). This situation resulted in a dominance of soil erosion on the four slopes with only a small amount of deposition. During the second half, February, March and April, the decrease of rainfall amount and available soil particles, because they had

Table 7.11 Mean monthly net loss for each slope (mm).

month	total for 36 pins each month				aver. net loss for 144 pins
	slope 1	slope 2	slope 3	slope 4	
Nov.	17.5	9.3	21.9	13.2	15.5
Dec.	10.2	6.9	16.3	11.1	11.1
Jan.	14.4	7.4	17.8	10.9	12.6
Feb.	11.2	4.8	11.9	9.4	9.3
Mar.	9.5	3.6	10.5	7.1	7.7
Apr.	7.3	2.8	8.4	4.3	5.7
Total	70.1	34.8	86.8	56.0	61.9

net loss=total loss - total deposition.

Table 7.12 Per cent of net loss for each slope in each month.

month	% of the total loss in each month				average % of total loss
	slope 1	slope 2	slope 3	slope 4	
Nov.	25.0	26.7	25.2	23.6	25.0
Dec.	14.6	19.8	18.8	19.8	18.0
Jan.	20.5	21.3	20.5	19.5	20.4
Feb.	16.0	13.8	13.2	16.8	15.1
Mar.	13.6	10.3	12.2	12.7	12.4
Apr.	10.4	8.0	9.7	7.2	9.2

been removed during the preceding months, as well as the improving vegetation cover, especially on cultivated slopes, resulted in very little overland flow, and so less soil material was transported. This can be further clarified by comparing the amount of erosion and deposition during November and April (Tables 7.10 and 7.11). As these tables show, soil loss in April was only 41.2% that of November, while the amount of soil deposited during the latter was as much as six times that of the former.

Table 7.13 Amount of rainfall, soil loss and deposition for each part of the season as per cent of the total.

part of the season	% of the total rainfall	% of total loss	% of total deposition
first part	62.4	61.1	14.9
second part	37.6	38.9	85.1

In terms of land use types, although the amount of rainfall was presumably similar for the four slopes, it was expected that naturally vegetated slopes would produce less runoff and, hence, lower rates of soil loss than cultivated slopes. This is mainly because an increase in runoff volume causes an increase in the detachment and transport capacity of the flow and hence an increase in soil loss (Roels, 1984). Consequently, cultivated slopes had 61.7% out of the total loss, only 28.7% of the total deposition, and 63.3% of the net loss. By contrast, naturally vegetated slopes had 38.3% of the total loss, 71.3% of the total deposition, and 36.7% of the net loss (Table 7.14). These differences in soil erosion and deposition between the two types are the result of the contrasting vegetation cover. However, both land use types have the same general pattern of soil erosion: that is, decreasing erosion and increasing deposition toward the end of the season. Although most of the soil loss on both land uses occurred during the first half, only 9% of the total deposition on cultivated slopes and 17.1% on naturally vegetated slopes occurred during the same period. This means that most of the deposition, especially on cultivated slopes, occurred after January and coincided with an improving, efficient vegetation cover.

Table 7.14 Monthly erosion and deposition by land use as a per cent of the total

month	cultivated		nat.vegn	
	removal	deposition	removal	deposition
November	15.2	1.7	8.9	2.6
December	10.2	-	7.3	2.6
January	12.5	.9	7.3	7.0
February	9.2	5.2	6.4	21.7
March	8.1	9.6	5.1	23.5
April	6.5	11.3	3.3	13.9
Total	61.7	28.7	38.3	71.3

7.6.2 Spatial patterns

The spatial patterns of soil erosion and deposition are generally characterised by erosion that is decreasing and deposition that is increasing downslope (Figures 7.5, 7.6, 7.7, 7.8 and 7.9). This pattern reflects the general influence of slope angle and, particularly, the influence of site angle. As Table 7.15 shows, the upper parts of the four slopes have steeper site angles and poorer vegetation cover than the lower slopes; therefore, upper slopes have higher rates of erosion and lower rates of deposition.

Table 7.15 Per cent of soil loss, soil gain, vegetation cover and mean of site angle by slope position.

slope position	% of soil loss	% of soil gain	% of veget. cover	mean of site angle (deg.)
lower	16.7	73.9	42.5	2.3
middle	37.2	4.4	37.5	3.8
upper	46.1	21.7	32.5	4.3

This trend, however, is not systematic, because of the variations within each slope. Some slopes have cases of deposition on their upper parts as well as erosion on their lower parts (see Figure 7.6b as an example). These variations are probably due to local topography and vegetation cover. Within each part of the slope are some flat locations with good cover; in these, even on upper slopes local deposition can occur. Furthermore, not all the soil material eroded from upper slopes was deposited on the lower slopes. A simple comparison between gain from deposition and loss from erosion shows that only 4.4% of the total eroded soil was redeposited on these slopes. Most of this material was distributed and deposited temporarily in different parts of the basin to be eventually carried to the sea. Because of this, most of the rain water that is carried by wadis to the sea, during flooding, has a red colour as a result of the large amount of soil material it transports.

It was slope 2, however, that had the lowest amount of soil removed, 16% of the total, and the highest gain, 54.7% of the total soil deposited (see Tables 7.11, 7.12 and 7.13, also Figure 7.9d and e). As explained earlier, this was attributable to the combined effect of good vegetation cover and small angle that this slope has. This situation was reversed on slope 3, where the highest loss (34% of the total) and the lowest gain (1.6% of the total) were recorded. Also, it is interesting to notice that slope 4, which has a relatively good cover of natural vegetation, has slightly different patterns of soil loss and gain from the other slopes. This slope gained the same amount of soil as slope 1 did, although the latter has a poorer vegetation cover. This is partially due to the fact that slope 1 is gentler and partially to the patchy nature of the vegetation cover of slope 4. However, the gain of soil on slope 4 generally increased toward the end of the season, while a high gain was recorded on slope 1 in the first month followed by a decrease then an increase from February. The relatively high gain on slope 1 in November (Table 7.10) is probably due to its small angle. A second possible reason is that some locations on slope 1 still have some straw, which, in turn, contributed to this gain.

7.6.3 Conversion of ground lowering values into weight per unit area.

In order to compare soil loss from the slope plots with that from similar areas, the values of surface lowering were converted into soil loss values as units of weight using an average bulk density of 1.5 g cm^{-3} (Tables 7.16 and 7.17). This bulk density value was used in similar studies conducted in Mediterranean areas (e.g. Francis, 1990; Jahn, 1989; Sala, 1988).

As Table 7.16 shows, the average ground lowering at the site was 1.8 cm, which is equivalent to 27 kg m^{-2}, as shown in Table

Table 7.16 Average surface lowering for the site and types of land use by slope position (cm).

Land use	by slope position lower	middle	upper	average by land use	average the site
Cultivated	1.2	2.4	2.9	2.2	1.8
Vegetated	0.5	1.5	1.9	1.3	

Table 7.17 The average surface lowering values after conversion into kg m^{-2} using a soil density of 1.5 g cm^{-3}.

land use	by slope position lower	middle	upper	average by land use	average the site
cultivated	18	36	43.5	33	27
vegetated	7.5	22.5	22.5	19.5	

7.17. This average of soil loss is within the range of what Young (1969) classed as accelerated erosion, which was of the order of 4.5 to 45.0 kg m^{-2} yr^{-1}. It must be remembered that the results obtained here are for a six month season, and not a complete year: nevertheless, because of the marked seasonality of rainfall, the great majority of the erosion in the year should have been observed. Moreover, this rate is higher than rates obtained from other Mediterranean environments (Francis, 1990; Gabert, 1964; Naveh, 1986; Romero-Diaz et al., 1988; Sala, 1988) (Table 7.18). Although most of these studies were conducted in similar environments, the rate of soil loss obtained by each study differs considerably. This is probably due in part to the techniques, equipment and the scale of measurements (e.g., small area, field plot or agricultural watershed) used in measuring soil loss (Lal, 1990) and in part to small-scale differences in land use, slope, etc.

Le Houerou (1981), in his study of soil erosion in the Mediterranean basin, which was based on the interpretation of

Table 7.18 Comparison between rates of soil erosion from different Mediterranean areas and the study area.

Study area	Author	Rate of * erosion kg m^{-2} yr^{-1}
Southern France	Gabert, 1964	10.7
South-eastern Spain	Francis, 1990	0.24
North Africa	Naveh, 1986	0.2 to 5.3
Murcia, Spain	Romero-Diaz et al., 1988	0.25
Montseny Mnt., Spain	Sala, 1988	19.5
North-eastern Libya	This study, 1995	27.0

* methods of determining soil loss differ.

aerial photographs, concluded that the amount of erosion is inversely proportional to the degree of afforestation, and this amount was higher in the south and east of the Mediterranean. In addition, in Mediterranean subtropical humid climates, intense rainstorms falling on ground poorly protected by vegetation can cause high rates of erosion (Saunders and Young, 1983). In North Africa, the amount of erosion ranges from 2 to 3 t ha^{-1} yr^{-1} (0.2 to 0.3 kg m^{-2} yr^{-1}) in areas with good vegetation, to 20 t ha^{-1} yr^{-1} (2 kg m^{-2} yr^{-1}) in areas cleared of vegetation, in some extreme cases, in Algeria, this amount was as high as 53 t ha^{-1} yr^{-1} (5.3 kg m^{-2} yr^{-1}) (Naveh, 1986).

The importance of land use and vegetation cover in controlling soil erosion and water runoff can be illustrated by comparing rates of soil loss from cultivated and vegetated plots. The average soil loss from cultivated plots is almost twice that from naturally vegetated plots. The importance of these factors can be further clarified by comparing average soil loss from upper vegetated slopes with that from lower cultivated slopes. Average soil loss from the former is only about 1.6 times that of the latter. This is a small difference, especially when we take into consideration that the upper slopes are areas of active erosion while lower slopes are areas of deposition.

If it is assumed that the 'normal' rate of soil erosion in this site is the rate of soil loss from vegetated plots, then the accelerated erosion rate is equal to the rate of soil loss from cultivated slopes minus the rate of soil loss under natural vegetation.

$$2.2 \text{ cm yr}^{-1} - 1.3 \text{ cm yr}^{-1} = 0.9 \text{ cm yr}^{-1}$$

This is equivalent to 13.5 kg m^{-2} yr^{-1}, which is still higher than the rates of soil loss obtained in most of the previous studies. Within the instrumented site, however, the average rate for naturally vegetated slopes is generally moderate, although the patchy vegetation of slope 4 has caused a slight increase in this rate. On the other hand the rate is high on the cultivated slopes and represents depletion of the soil resource, especially when it is considered that the soils of the studied sites are so shallow that they can hardly tolerate any further loss, and that the amount of rainfall during the study period was much lower than the average. Moreover, if the current rates of soil erosion and runoff, especially on cultivated upper slopes where the soils are shallow, are allowed to continue, the soils and water resources will be damaged beyond recovery within a short period of time. This implies that a soil conservation programme should be implemented, at least in the most affected locations if not for the whole study area.

7.6.4 Conclusion

According to the results obtained from soil loss measurements, at the instrumented site, cultivated areas have the highest rates of soil loss, while naturally vegetated areas have the lowest. This is mainly due to the degree of protection against erosion that each type provides. However, areas of dry grass and those cleared of natural vegetation are similar to cultivated areas in terms of protection against erosion. Therefore, by calculating the frequency of cultivated and naturally vegetated areas and their distribution according to slope position in the studied sites, the locations of high erosion rates can be identified (Table 7.19).

As Table 7.19 shows, the lower and the middle slopes have the highest frequency of land uses that provide less protection against erosion. Thus, these locations can be expected to have high rates of erosion. This assumption also agrees with the fact

Table 7.19 Frequencies of land use types by slope position (the studied sites)

type of land use	slope position		
	lower	middle	upper
natural vegetation	6	9	20
cultivated	45	30	17
others	9	21	23

cultivated=wheat/barley, dry grass and cleared areas.
others=fruit tree and vegetable areas

that these locations recorded the highest frequency of erosion features. Consequently, more attention should be paid to these locations in terms of soil and water conservation. However, some of the previous results (Chapter 6) also showed that some cultivated areas were well protected by sufficient plant residues (straw) or a good cover of grass. Thus, rates of soil loss are expected to be low. On the other hand, some naturally vegetated areas, where vegetation is affected by heavy grazing, are expected to have high rates of soil loss.

Slope 1

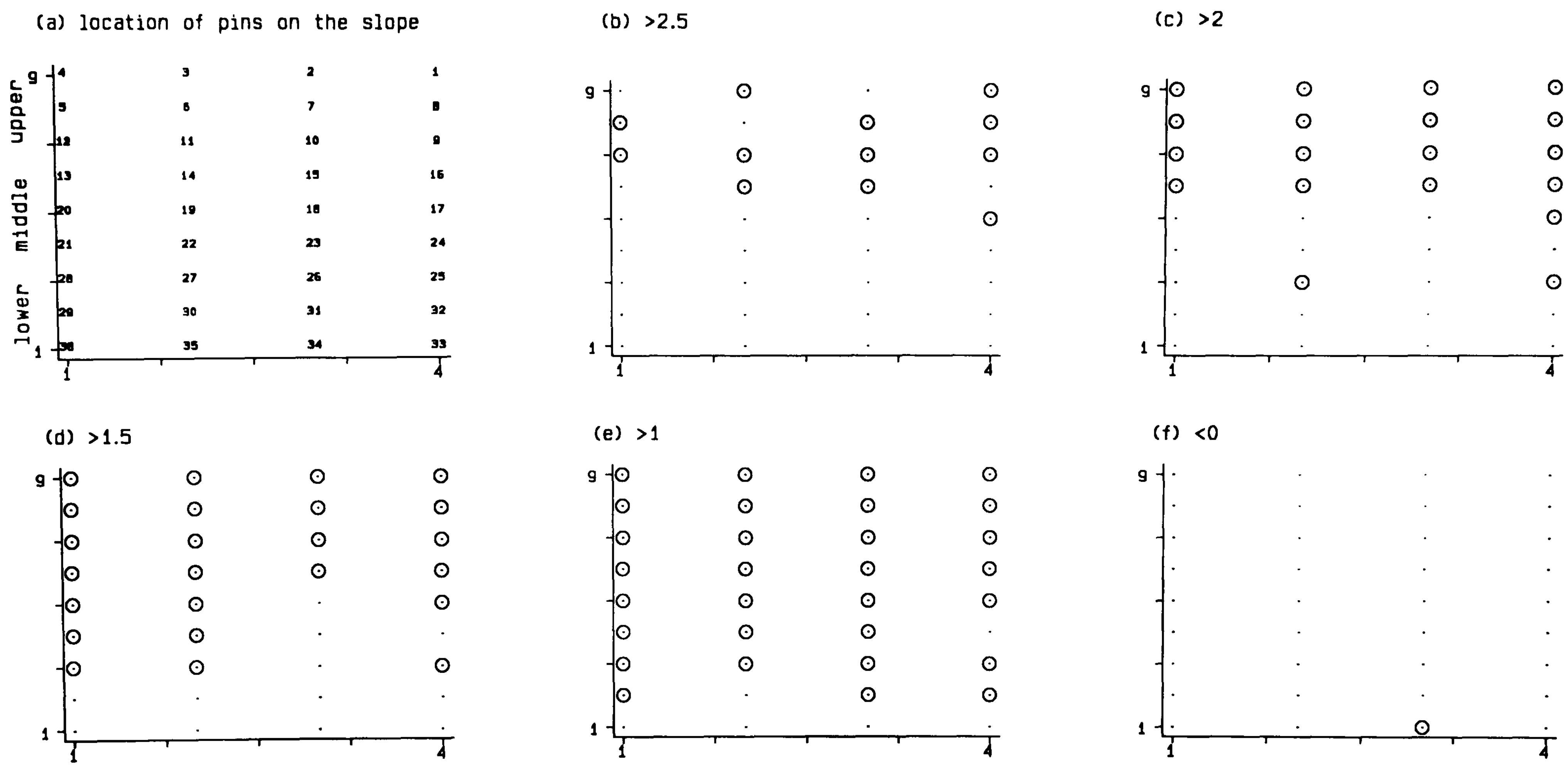


Figure 7.5 Patterns of soil erosion and deposition (mm)

Slope 2

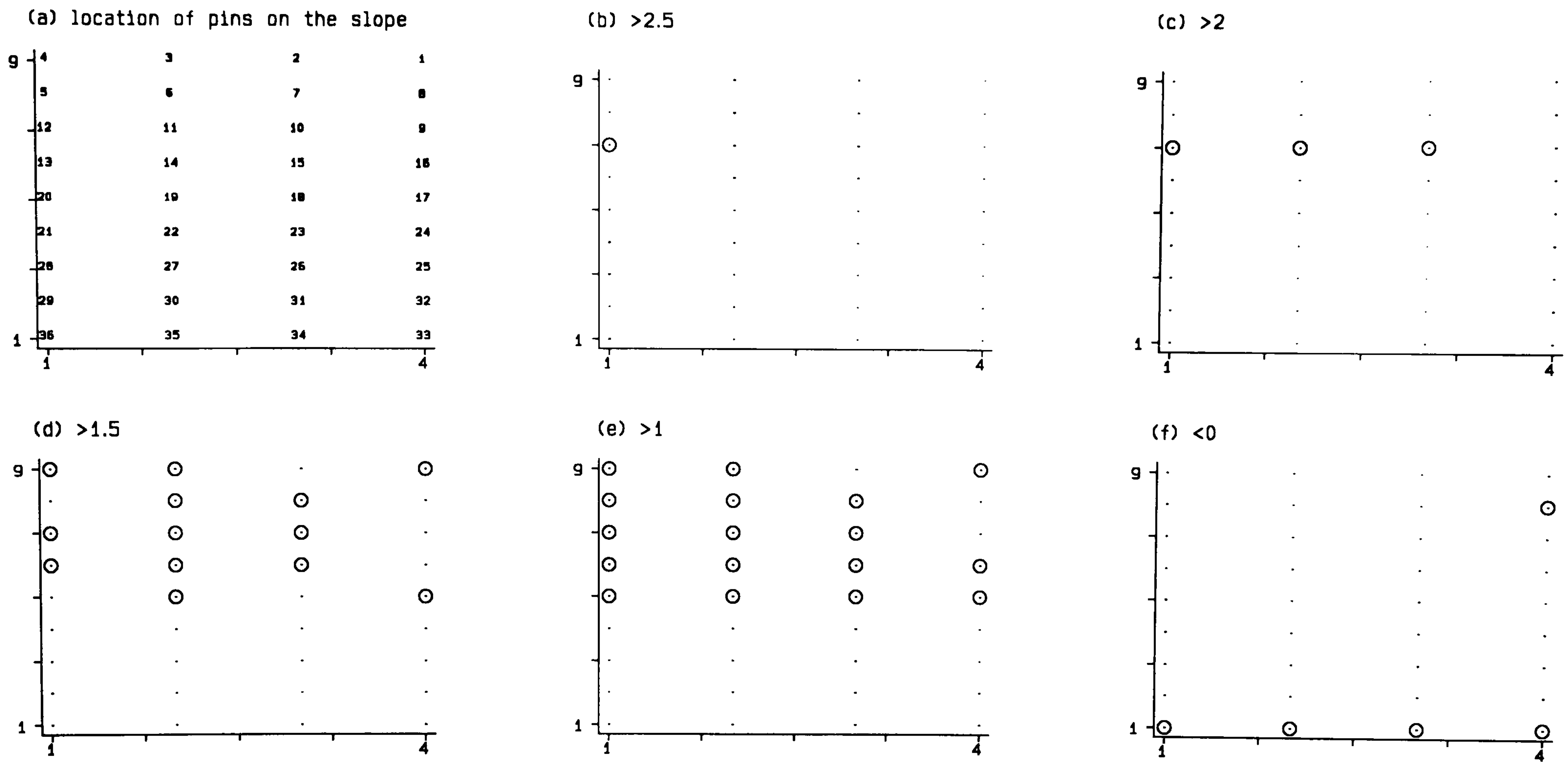


Figure 7.6 Patterns of soil erosion and deposition (mm)

Slope 3

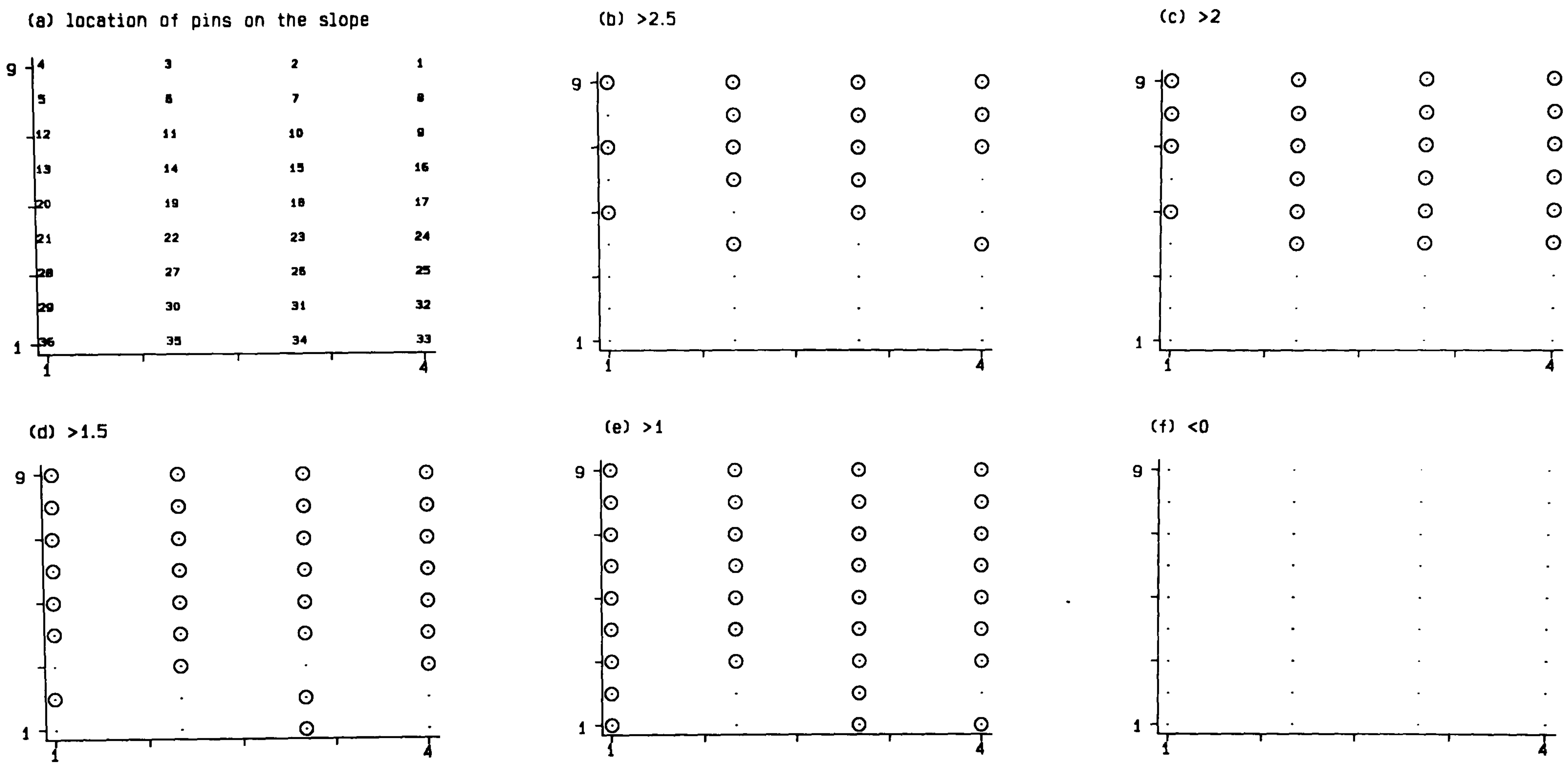


Figure 7.7 Patterns of soil erosion and deposition

Slope 4

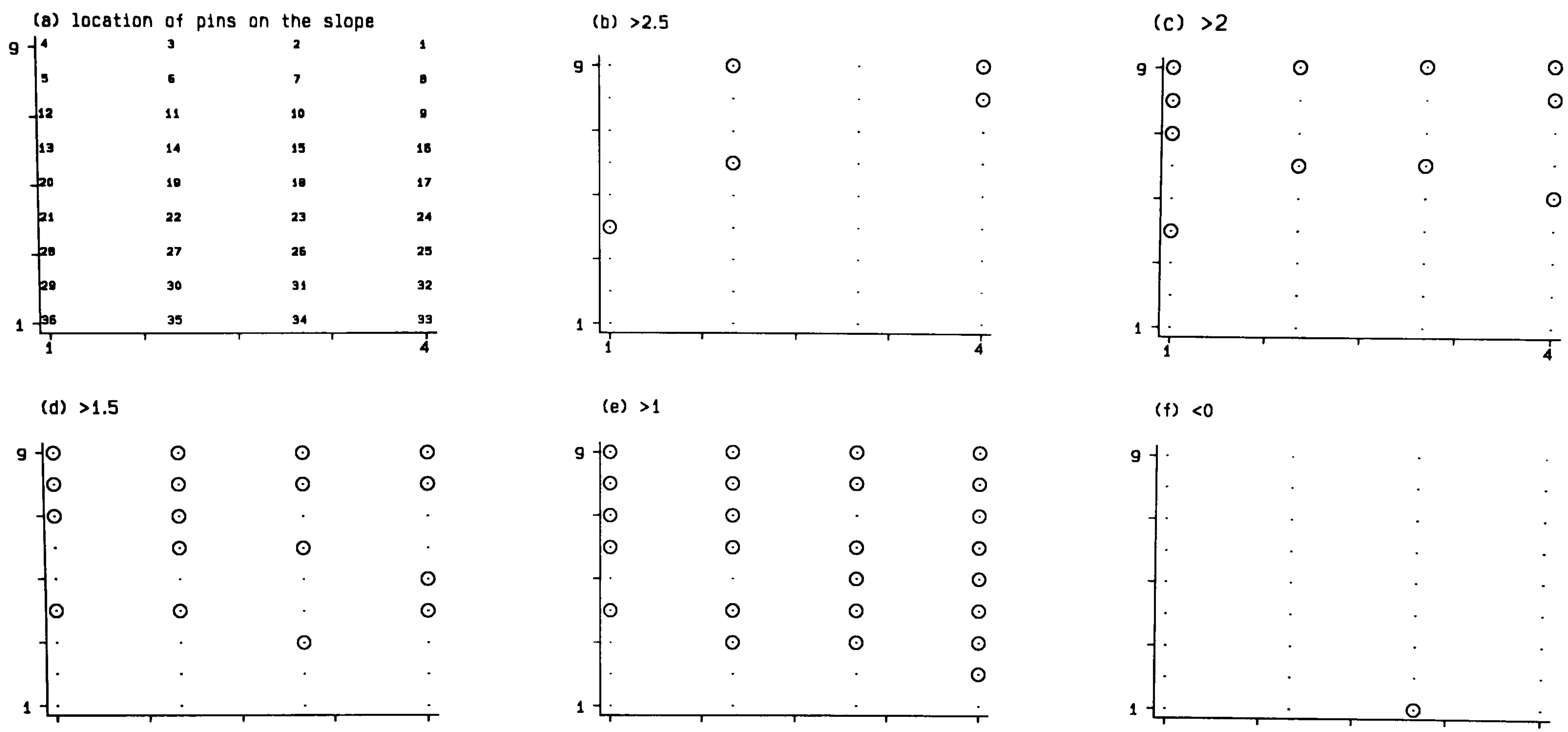


Figure 7.8 Patterns of soil erosion and deposition

The four slopes

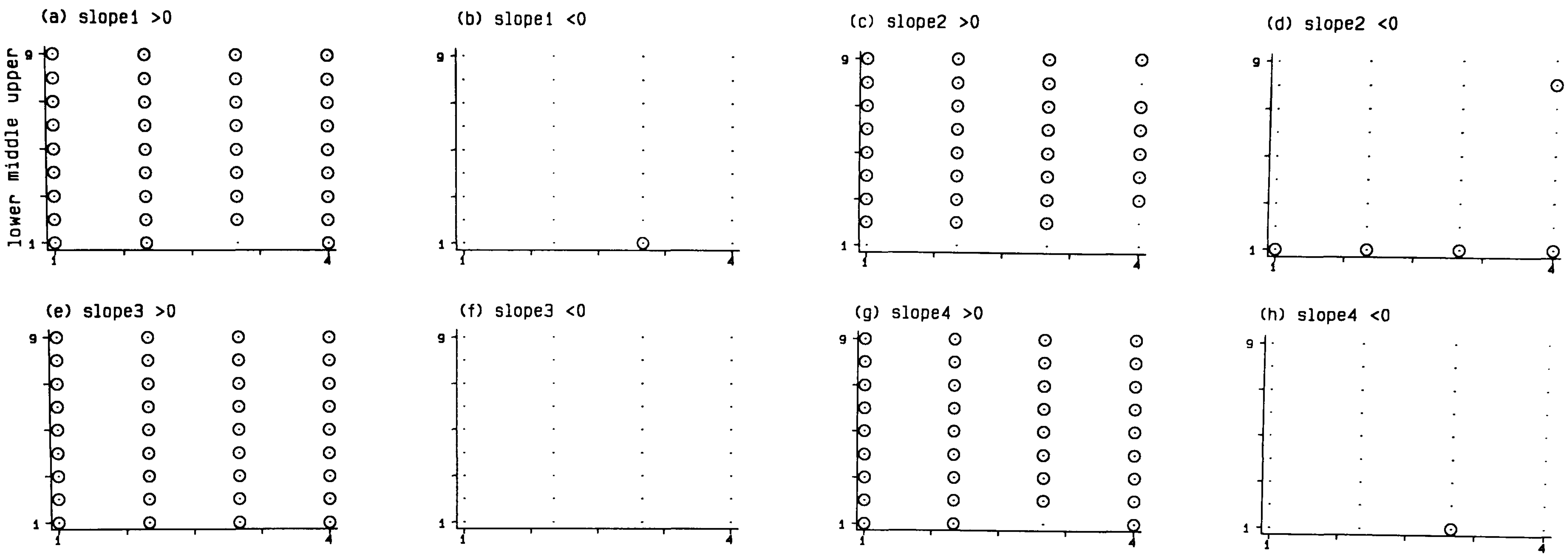


Figure 7.9 Patterns of absolute erosion and deposition (mm)

Chapter 8

Soil erosion factors and features and their controls

8.1 Introduction

In most soil erosion studies it is apparent that several controlling factors exert an influence on the incidence and rate of erosion (Morgan, 1986; Driessen, 1986; Dudal, 1981 and Sanders, 1988). In this study, a wide range of data were collected on the factors that influence soil erosion by water. These data are classified into four main factors and each factor is further divided into sub-factors (Table 8.1).

Table 8.1 Factors related to soil erosion in the study area.

main factors	sub-factors
1. soil erodibility	a. soil texture b. organic matter content c. infiltration rate d. soil depth
2. topography	a. slope length b. slope steepness c. slope position d. site angle e. Kennedy integral
3. erosivity	a. amount of rainfall
4. land use	a. per cent of vegetation cover

Most of these variables can be measured on continuous scales, although some are essentially categorical, such as soil texture and slope position. The main technique for data analysis is therefore multiple regression. However, as will be seen in the third section of the chapter, a very different approach is needed to discuss the presence and absence of soil erosion features, such as gullies, rills and concentrated flow. Careful study of soil loss and the distribution and intensity of erosion features indicates that only a few of the factors listed in Table 8.1

exert the greatest control. These important factors are shown in Table 8.2.

Table 8.2 Variables identified as the most important in controlling soil erosion by water in the study area.

main factors	the most important factors
1. soil erodibility	a. infiltration rate b. soil depth
2. topography	a. slope steepness b. site angle c. Kennedy integral
3. erosivity	a. amount of rainfall
4. land use	a. per cent of vegetation cover

In order to identify the importance of each variable the following procedure was adopted:

1. These variables were divided into controlling and response variables (Table 8.3). However, rainfall cannot be included as a factor in the data analysis. There are only six values of monthly rainfall, and since rainfall was only measured at one gauge it cannot be included in the regression analysis or used as a factor explaining spatial variations between sites.
2. Regressions were carried out with two variables at first. After putting the residuals from regression in a new variable, the additional variable that is most strongly correlated with the residuals is included in the regression.
3. The previous procedure (step 2) is repeated to identify and add another new variable. The most important variable is one that brings the highest change in R^2 and RMS error.
4. The production of a graph showing the best estimates of the linear effects of each controlling variable on the response.

Table 8.3 Controlling and response variables.

controlling variables	response variables
1. slope steepness 2. site angle 3. Kennedy integral 4. per cent of vegetation cover	1. infiltration rate 2. soil depth 3. per cent of vegetation cover

The relationships between these factors, the controlling variables x_1, x_2, etc. and the response variables, y, are thus analysed using multiple regression. Predicted values of y are given by the linear equation

$$\hat{y} = a + b_1x_1 + b_2x_2 + b_3x_3 + \ldots$$

example. predicted value of IR
= constant + coeff x pcc
+ coeff x siteangle
+ coeff x st
+ ...

IR=infiltration rate pcc=per cent of vegetation cover
st=slope steepness

The coefficient of determination R^2 is the proportion of the variance of y accounted for by the regression. It measures the goodness of fit of the equation to the data, varying between 0 and 1 (or 0 and 100%). The root mean square (RMS) error is essentially the standard deviation of the residuals and so is measured in the same units as the response variable. In addition the individual residuals were inspected in assessing the regression results. In this study, the reduction of RMS error and increase of R^2 are the criteria used to identify the importance of controlling variables in controlling the response or dependent variable. The degree of fit was improved by adding more x variables: however, in practice it is usually the case that diminishing returns set in after the most important have been included. The major concerns are with the level of explained variation as represented in the R^2 and RMS error, and in deciding which variables contribute substantially to the regression.

In the multiple regression analyses, some variables that are used are essentially proxy or surrogate variables; that is what can be measured is used as a substitute for some other variable that is difficult or impossible to measure, at least on a continuous scale. Thus 'soil depth' is of interest in its own right, but is also used as a partial measure of soil erosion: other things being equal, the more erosion, the thinner the soil. Similarly, if 'slope length' appears as a controlling variable, this may be not so much because it is of direct importance, but also because it stands proxy for properties such as land use that are found to vary between short and long slopes for a combination of reasons.

8.2 Regression of response variables

8.2.1 Infiltration rate

Infiltration rate is a very important factor in the process of soil erosion by water. It controls the generation of runoff, which is the most important agent in water erosion. However, due to the fact that clayey texture is dominant at most of the sites, infiltration rates were expected to be low. The highest rate at any site was 15 cm hr^{-1} and the lowest was 0.8 cm hr^{-1}, the overall mean was 5.3 cm hr^{-1} with a standard deviation of 3 cm hr^{-1} (Figure 8.1).

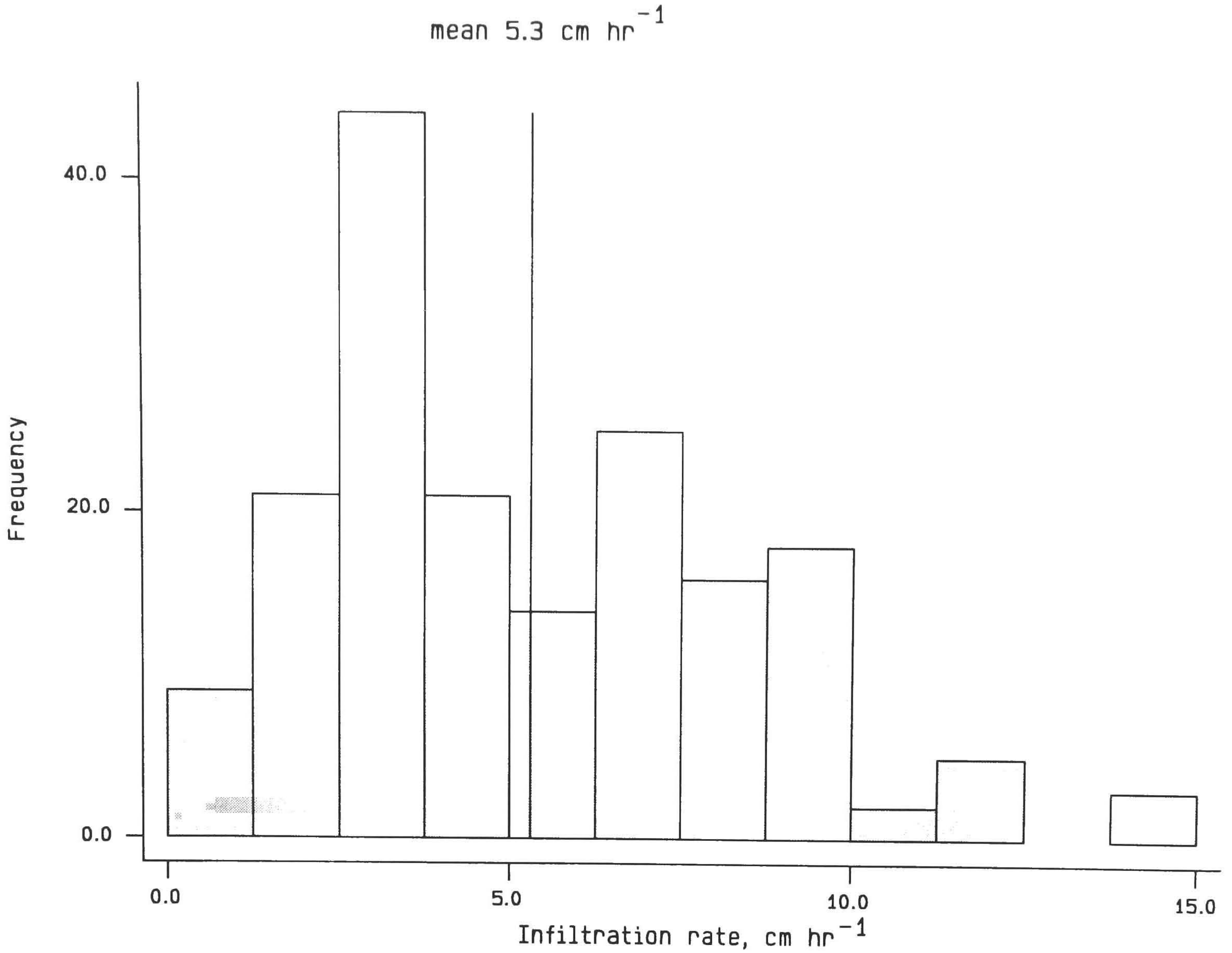


Figure 8.1 Frequency distribution of infiltration rate

In this study, rates of infiltration were mainly influenced by factors such as per cent cover, slope length, site angle and to a lesser degree, slope steepness and soil depth). In addition, it was per cent of vegetation cover and slope length that brought major changes in RMS error and R^2, while slope steepness and soil depth brought only a slight change (Table 8.4 and Figure 8.2).

Table 8.4 Multiple regression of infiltration rate on various possible controlling variables.

step	variable	relation with IR	R^2	RMS error
1	per cent cover	+	0.198	2.689
2	slope length	-	0.300	2.520
3	site angle	+	0.328	2.475
4	soil depth	+	0.344	2.454
5	slope steepness	+	0.363	2.425

R^2=coefficient of determination RMS=root mean square error

Figure 8.2 shows the scatter plots for infiltration rate and the five variables that were included in the multiple regression. The regression lines for the bivariate relationships are shown. (The predicted values are shown for all the data, including locations where infiltration rates could not be measured because of inaccessibility. This explains the graph for infiltration and site angle (Figure 8.2c) with the regression line boldly traversing an area of the graph apparently free of data, but in reality only lacking the infiltration rate data). The strength of the individual bivariate relationships is not the same as the 'importance' of the particular controlling variable in the multiple regression. The first takes no account of any other variables, whereas the second is influenced by the other variables in the multiple regression.

The regression of average infiltration rate on per cent cover shows a moderate positive relationship, in which cases with high infiltration rates tend also to have high per cent of vegetation cover (Figure 8.2a). Generally, a good vegetation cover can affect infiltration rate directly by reducing runoff velocity, allowing more time for infiltration, and indirectly by increasing the organic matter content of the soil and promoting a more open soil structure, which in turn increases the rates of infiltration. However, the scatter plot shows some variability in this relation. Most of this variability can be explained in terms of soil properties, soil characteristics and type of land use. Some locations have low infiltration rates and high per cent cover values, while others combined high infiltration rates and low per cent cover values. The former may be attributed to the influence of texture, as most of the former cases have soils of fine textures, while the latter are generally attributable to the influence of coarse texture, cracking, ploughing or loosening of the soil.

Slope length shows a moderate negative relationship with infiltration rate, implying that long slopes tend to have low infiltration rate values (Figure 8.2b). In order to identify the differences between long and short slopes, these slopes were divided into two groups. These are: group 1, which comprises the slopes that are longer than 355 metres, which is the mean length of the studied slopes; and group 2, which comprises the slopes that are shorter than the mean. The slopes of group 1 are generally characterised by lower per cent cover, finer soils, more compaction and gentler slopes than the second group. All these characteristics are similar in that they can reduce infiltration rates, a fact that is clearly reflected in the relationship between slope length and infiltration rate. In addition, this difference in infiltration rates between the two groups can be explained in terms of soil type. About 67.7% of the slopes of group 1 are covered by vertic brown and red compacted soils. These two soil types record the lowest infiltration rates because of their generally fine textures and compaction. These soils cover 32.3% of the slopes of group 2.

Most of the variability in this relation is due to the differences in soil properties and characteristics and the type of land use of each case. Cases that show high rates of infiltration on long slopes are influenced by cracking, ploughing or high per cent cover, while those with low rates of infiltration and located on short slopes mostly have fine-textured soils.

There is a weak positive relationship between site angle and infiltration rate, in which the infiltration rates slightly increase with the increase of site angle (Figure 8.1c). The variability in this relationship can be explained in terms of soil texture and per cent cover. Most of the gentle parts of the slopes are cultivated areas characterised by fine texture and poor cover, while those of steep angles are naturally vegetated, have coarse textures and high per cent cover, and therefore record high infiltration rates. However, some locations show relatively small angles and high rates of infiltration; these are mainly affected by cracks.

The relationship between soil depth and infiltration rate is rather weak, where infiltration slightly increases with soil depth. The points are so scattered and the regression line almost horizontal, showing almost no effect of soil depth on infiltration rate (Figure 8.2d). This weak relation is mainly attributed to the fact that most of the locations of deep soils are cultivated areas that combine poor cover and fine textures.

This relation is stronger with the mean of slope steepness, with infiltration rates that generally increase with slope angle (Figure 8.2e). This positive relationship reflects the fact that most of the steep slopes are naturally vegetated with good vegetation cover and coarse textures, while the few locations on these steep slopes that record low infiltration rates mostly have relatively poor vegetation cover and fine textures.

8.2.2 Vegetation cover

Vegetation cover is an important factor in controlling soil erosion by water. It protects the soil directly by intercepting raindrops and absorbing their kinetic energies and by reducing surface water velocity, and indirectly by improving infiltration rate. A well vegetated area with a permeable soil will experience higher infiltration, lower surface runoff, and less surface erosion (Selby, 1993). Furthermore, vegetation cover can be dealt with as an indicator of erosion. Patches of bare ground or poor

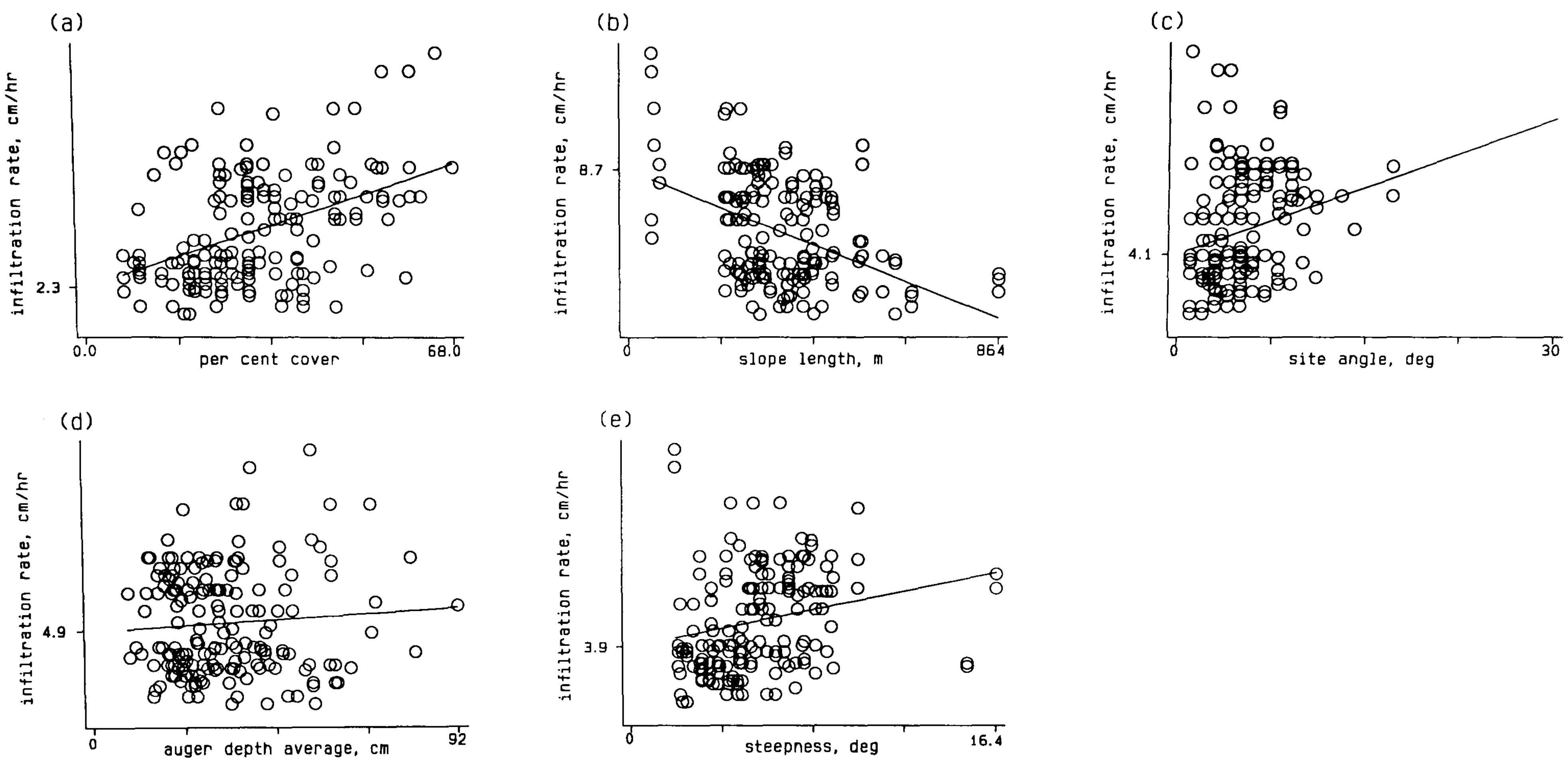


Figure 8.2 Regression of infiltration rate on controlling variables

vegetation cover are where erosion usually takes place.

The vegetation cover of the sites varied from 7% to 68%, with a mean of 31.7% and a standard deviation of 13.8% (figure 8.3). The variability of per cent cover is mainly related to land use type. Cultivated areas usually have poorer vegetation cover (mean 27.7%) than naturally vegetated areas (mean 41.7%). Land use type and hence percent of vegetation cover are mainly controlled by soil depth, slope steepness and site angle (Table 8.5). The latter is the average angle of each part of the slope. Therefore, steep slopes and steep parts of the slope with shallow soils are usually naturally vegetated areas and hence have good vegetation cover. In contrast, gentle slopes or parts of the slope with relatively thick soils are cultivated areas and mostly have poor vegetation cover.

Table 8.5 Multiple regression of per cent vegetation cover on various possible controlling variables.

step	variable	relation with pcc	R^2	RMS error
1	site angle	+	0.037	13.592
2	slope steepness	+	0.038	13.620
3	soil depth	-	0.038	13.656

(for key see table 8.3)

There is a negative relationship between per cent cover and soil depth: i.e., a slight decrease in per cent cover with the increase of soil depth (Figure 8.4a). This is mainly attributable to the fact that most of the cultivated lands, which are generally characterised by poor cover, are located in areas of relatively deep soils. Mean soil depth for cultivated areas is

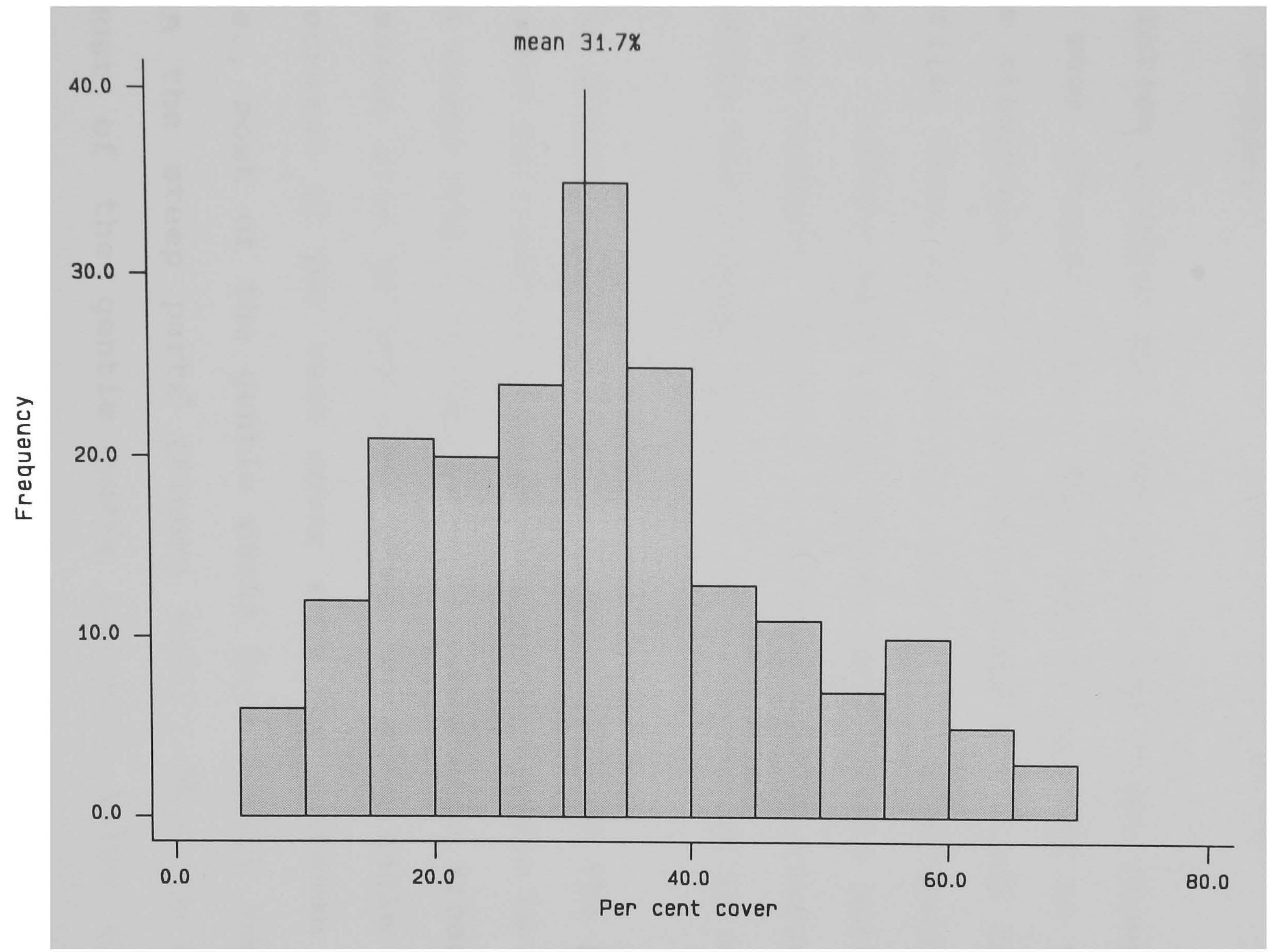


Figure 8.3 Frequency distribution of per cent vegetation cover

38.7 cm and 27.6 cm for naturally vegetated (Table 8.6).

Table 8.6 Means of some properties of cultivated and naturally vegetated areas.

type of land use	pcc (%)	sd (cm)	s.angle (deg)	st (deg)	pcc for each sp. L	M	U
nat.vegn	41.7	27.6	7.3	5.9	12.5	17.2	34.4
cultivated	27.7	38.6	4.5	4.9	87.5	82.8	65.6

nat.vegn=natural vegetation pcc=per cent vegetation cover
sd=average soil depth s.angle=site angle
st=slope steepness sp.=slope position L=lower
M=middle U=upper

The relation between per cent cover and slope steepness is also very weak (Figure 8.4b). This may be related to the fact that slope steepness, which is the average angle for the whole slope profile, does not show the angles for each part of the slope; i.e., within each steep slope, some gentle parts could be found. For example, slope 7 at Shahhat has an average angle of 16.4° while the average angle of its lower slope is only 7°.

The site angle, which is positively related to the per cent cover, is more relevant in this case. Mean site angle is 4.5° for cultivated areas and 7.3° for naturally vegetated areas. Thus, the regression line of per cent cover on site angle shows a general increase of per cent cover with the increase of site angle, i.e., most of the gentle parts have poorer vegetation cover than the steep parts (Figure 8.4c). This is probably because most of the gentle parts of each slope represent cultivated areas, while most of the steep parts are naturally vegetated areas. However, variations of per cent cover can be found within each area. For example, as the scatter plot shows, some areas of small angles recorded good vegetation cover. These are mainly cultivated areas that have large amounts of straw left on the soil surface. Equally some of the gentle areas are naturally vegetated and have good cover, and they are not cultivated, because of their location on upper slopes, which made them inaccessible. Conversely, there are some parts with steep angles and poor vegetation cover. These are either natural vegetation areas affected by heavy grazing or very steep parts (cliffs) that have very shallow soils or rocky surfaces; therefore their vegetation cover is very poor.

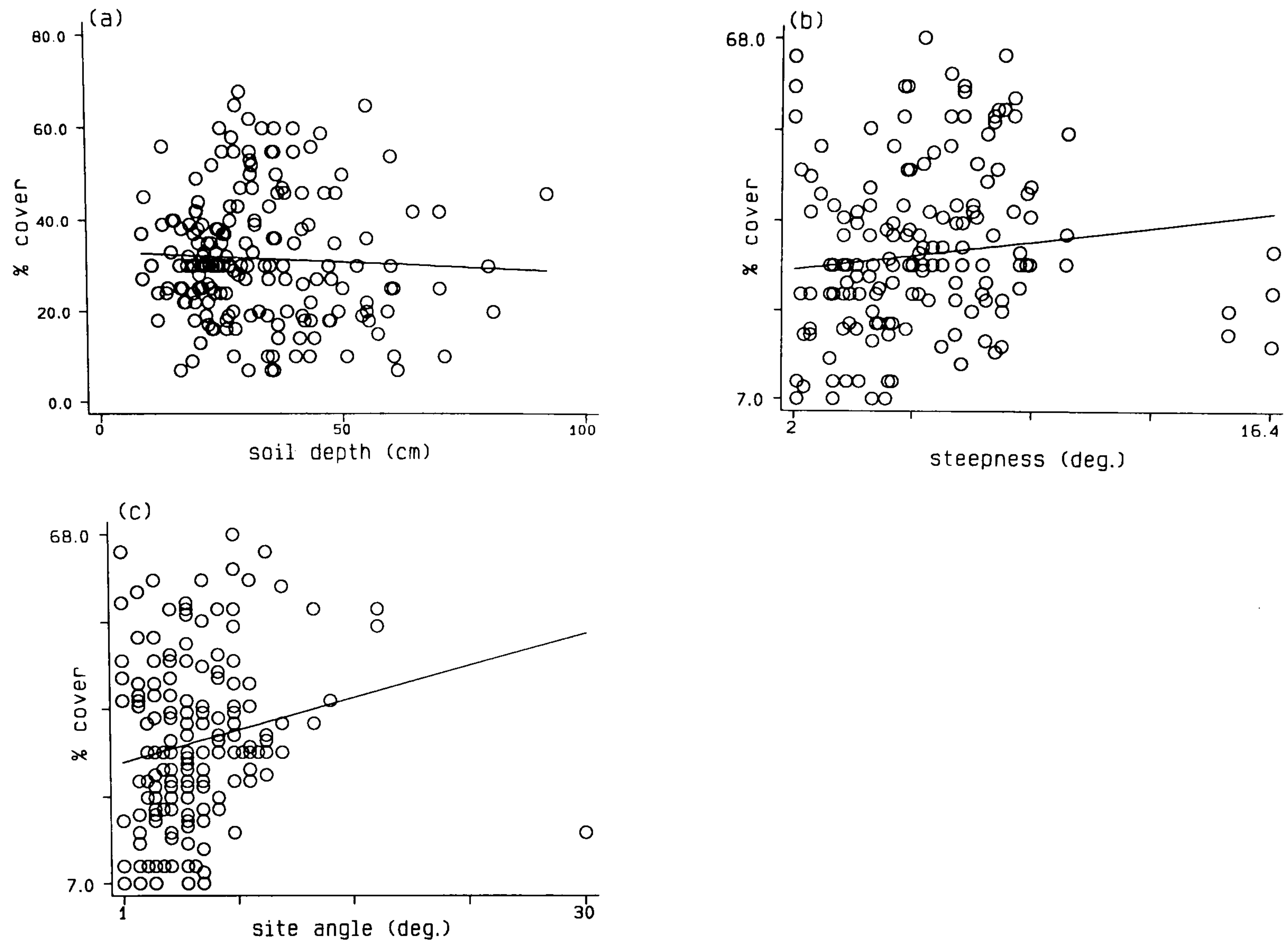


Figure 8.4 Regression of per cent vegetation cover on controlling variables

8.2.3 Soil depth

The five auger measurements were summarised in terms of average, minimum and maximum. The range of auger measurements at each site is generally rather small and itself varies from 3 cm to 53 cm, with a mean of 15.5 cm and a standard deviation of 9.8 cm (Figure 8.5). The uncertainty associated with the mean depth at each cross profile can be measured by the standard error of the sample mean. Appendix 4 provides a test of the mean and standard errors of the depth measurements at every sample location at each site.

Soil depth can be viewed as a function of slope steepness, Kennedy integral, slope length, site angle and per cent cover. However, it is best related to slope steepness, Kennedy integral and site angle, while slope length and per cent cover did not bring any substantial change to R^2 and RMS error (Table 8.7). In addition, their regression lines show virtually horizontal slopes (Figure 8.6c and e).

Table 8.7 Multiple regression of soil depth on various possible controlling variables.

step	variable	relation with S.D.	R^2	RMS error
1	slope steepness	-	0.1375	13.982
2	Kennedy	-	0.1460	13.950
3	slope length	-	0.1497	13.957
4	site angle	-	0.1534	13.963
5	per cent cover	-	0.1536	13.999

S.D.=soil depth

Slope steepness shows a negative relationship with soil depth, so that average of soil depth decreases with increasing slope angle (Figure 8.6a). This relation agrees with what previously

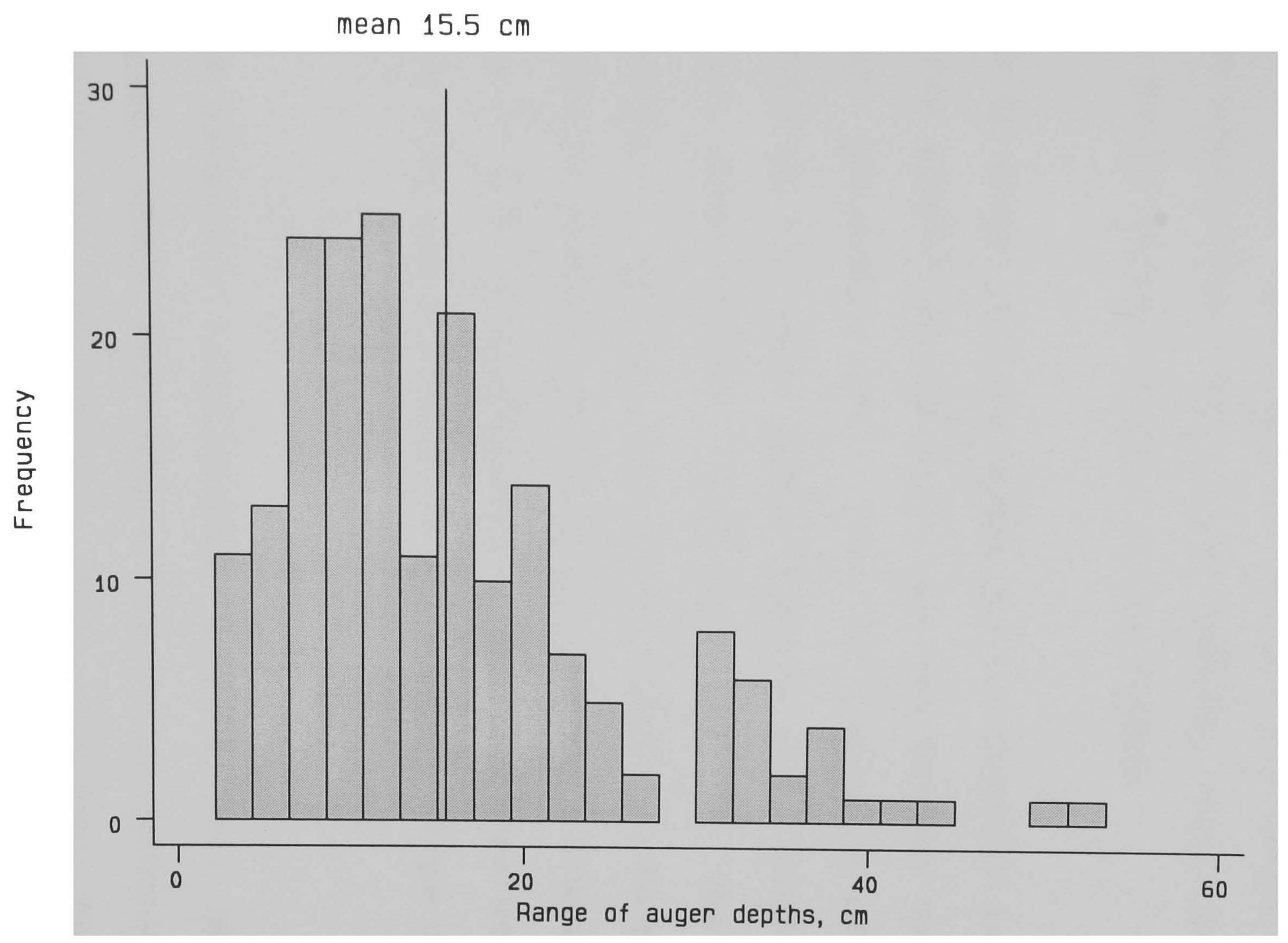


Figure 8.5 Frequency distribution of soil depth

mentioned that steep slopes increase runoff and rates of erosion and the result is thin and weakly developed soils. However, much of the variability can be explained in terms of local factors along each slope. Local factors such as a horizontal part of a slope could be found on a generally steep slope, resulting in the development of a relatively deep soil. Furthermore, on such a horizontal part, soil depth could be further increased by a good and continuous vegetation cover. Such factors, also, can create cases of thin soils on relatively gentle slopes.

The effects of slope profile shape may be assessed in various ways. One fairly simple method is to use the Kennedy or height-length integral (Kennedy, 1967). This is a measure of profile shape calculated as the area under the hillslope profile as a fraction of the area of the bounding rectangle. The measure varies from nearly 0, for a highly concave profile, to nearly 1, for a highly convex profile. A perfectly straight profile would have a measure of 0.5. A predominantly convex slope would have a measure above 0.5, and a predominantly concave slope one below 0.5.

There is a negative relationship between soil depth and Kennedy integral, where soil depth generally decreases with increasing Kennedy integral (Figure 8.6b). However, there is a great deal of scatter on a plot of average soil depth against the Kennedy integral, but a relationship may nevertheless be identified. It is most obvious in the low soil depths for the most convex slopes. This is in response to the fact that convex slopes are often areas of active erosion process; thus, soils are usually shallow. In contrast, concave slopes are often areas of active deposition, leading to accumulation of soil material. This relation between slope form and soil depth can be further clarified when the slopes are divided into two groups, group 1, convex slopes, which have Kennedy integral of more than 0.5, and group 2, concave slopes, with Kennedy integral of less than 0.5. The first group, where the slopes are generally convex, recorded shallow soils (mean of 28.6 cm), while the mean soil depth of the slopes of group 2 is 36.8 cm. For the four steepest profiles, with measures above 0.7, the mean soil depth is 18.4 cm, compared with the mean for all slope profiles of 32.2 cm.

However, some slopes of relatively low Kennedy integral showed shallow soils. Although these slopes are concave in their general shapes, some of their parts are relatively steep, and therefore have shallow soils. The shallow soils of these parts pulled down the average soil depth in these slopes.

The relationship between the average auger depth and the site angle is both interesting and important. The scatter plot shows a triangular pattern, which is easy to interpret as showing the lack of deep soils on steep slopes, but also the variability of soil depths on gentle slopes (Figure 8.6d). This variability is not surprising given the range of conditions that would be found on slopes of a given angle. There could be gentle slopes on upper convexities and gentle slopes on lower concavities that would be expected to have very different regimes of erosion and deposition. In addition, despite relatively high variability, the average soil depth is somewhat greater on lower slopes (mean 34.5 cm) and middle slopes (33.7 cm) than on upper slopes (mean 28.4 cm).

The regression of average soil depth on site angle, however, literally implies only a fairly weak relationship. This may be attributed to the fact that we are fitting a straight line to a triangular pattern, which is likely to be only a limited success. Some of the scatter in the relationship between average soil depth can be explained in terms of slope position. Here, most of the lower slopes have small angles; thus, their soils are generally deeper than upper slopes which are generally steeper. Much of the variability is in fact better considered as a reflection of the variability between areas, for example the range from the mean for Magra (21.8 cm) to the mean for Al-Kouf (52.9 cm). If we focus on the sites with angles up to 5 degrees (117 out of 192), the range is from the mean for Magra (21.3 cm) to the mean for Al-Kouf (54.5 cm). However, the relationship between site angle and soil depth is more or less similar to that between slope steepness and soil depth. The difference is that this relation is more detailed in the former because site angles are the detailed angles within the slope. Therefore, there is less variability in the relation of soil depth and site angle.

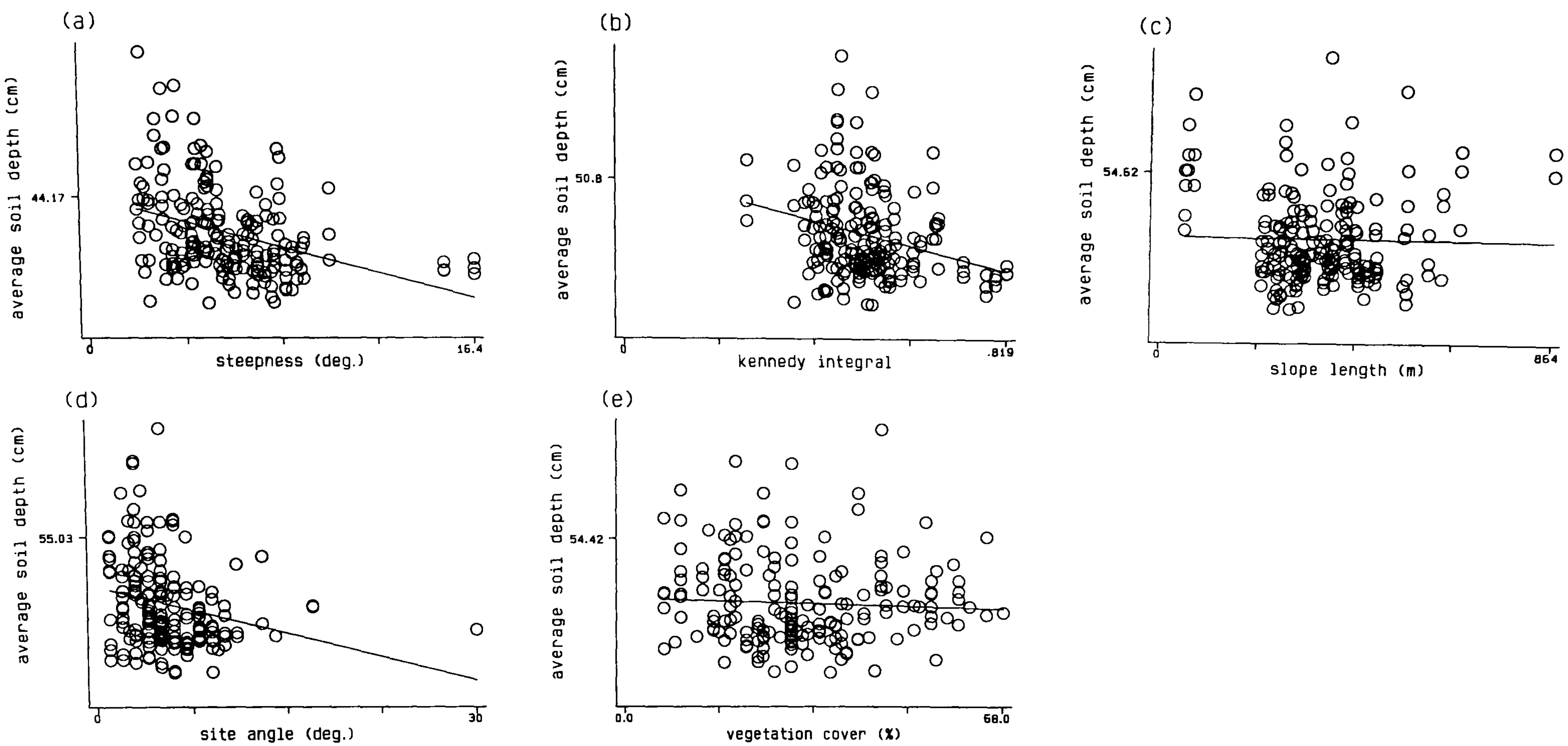


Figure 8.6 Regression of soil depth on controlling variables

8.3 Soil erosion features

The presence of gullies, concentrated flow and rills was noted when carrying out the main profile survey, and measurements were made of gully length, width and depth (Table 8.11) (also see Chapter 4, section 4.2.4). However, discussion will be mainly in terms of controls on the presence or absence of gullies, concentrated flow and rills. The main results for length, width and depth of gullies will be noted briefly. In addition, these features can not be included in the multiple regression because of the following reasons:

1. Because of the small number of these features, the available data are not enough for multiple regression.
2. Since the great majority of gullies occur at the base of the hillslope profile, their sizes are not expected to be a direct result of the precise properties of the adjacent hillslope.

Soil erosion features, such as gullies, concentrated flow and rills, were found at all sites, with the exception of Al-Kouf and Gobba, and on all four soil types. However, these features tended to be more frequent on ferric red compacted soils and at sites where the vegetation cover is poor, such as Magra, or where the slopes are relatively steep, such as Shahhat, Batta and Magra. The frequency of these features is further increased at sites combining poor cover and steep slopes and having ferric red compacted soil, such as Magra site (Tables 8.8 and 8.9). Furthermore, in Magra and Bayyada sites, some of these features were increased in number and size by human activity, especially road construction.

Because of the generally poor vegetation cover and the fine texture of the soils of the study area, these features, rills in particular, were expected to be more frequent (Gerrard, 1981).

Table 8.8 Frequency of soil erosion features and means of slope angle and per cent of vegetation cover at each site.

site	number of gullies	rills	cfl	steepness (degrees)	pcc (%)
Lussaita	3	1	6	6.8	33.5
Bayyada	2	5	4	3.8	21.1
Batta	3	3	7	7.1	49.3
Magra	6	6	6	6.2	25.6
Gobba	-	1	-	3.8	26.6
Shahhat	5	4	6	8.0	31.4
Al-Kouf	-	-	-	3.6	37.5

cfl=concentrated flow

This was probably due in part to the time of survey. Field study was after harvest, so most of the old rills have probably been obliterated, and before the start of the new rainy season when new rills would develop.

Although there are some differences between these features, they are similar in that they are, more or less, influenced by the same factors. The presence of soil erosion features is mainly related to slope shape, slope steepness and per cent of vegetation cover.

In general, these features, and gullies in particular, were mainly confined to cultivated areas on lower slopes (Tables 8.9). Such areas, when compared with other lower slope areas where these features are absent, are mostly located on slopes that have general convex shape, are relatively steep and have poor vegetation cover (Tables 8.10a, b and c, and Figure 8.7). Here runoff velocity, as well as its erosivity, is expected to increase. Furthermore, the relatively deep soils of these areas made them more susceptible to gully erosion (Bocco and Garcia-Oliva, 1992).

Table 8.9 Distribution of erosion features according to type of land use, slope position and soil type.

erosion feature	land use type				s.position			soil type			
	nv	wb	dg	ft	L	M	U	fr	frc	fb	vb
gullies	-	10	6	3	15	3	1	6	8	3	2
rills	4	7	5	4	4	13	3	3	11	3	3
cfl	3	14	8	4	16	9	4	10	10	7	2

nv=natural vegetation wb=wheat and barley dg=dry grass
ft=fruit trees
L=lower M=middle U=upper
fr=ferrous red soil frc=ferrous red compacted fb=ferrous brown
vb=vertic brown

However, rills were recorded under both naturally vegetated and cultivated areas, with higher frequency under the latter (Figure 8.8). As with gullies and concentrated flow, rills are generally associated with relatively steep slopes that have convex forms and poor vegetation cover. Unlike gullies and concentrated flow, however, rills are mainly found on the relatively steep middle slopes, where the soils are compacted in most cases and the average site angle is higher than the average angle of the slopes (Table 8.10b).

Concentrated flow combine the characteristics of gullies and rills. They are found under both cultivated and naturally vegetated areas, and they also tend to be more frequent on lower relatively gentle slopes (Figure 8.9).

Table 8.10 Means of some properties of areas where erosion features are found compared with those free of these features.

(a) gullies

erosion feature	per cent cover (%)	steepness (degrees)	Kennedy integral	site angle (degrees)
gullies	26.4	7	0.57	4.8
no	31.8	5.8	0.52	5.6

(b) rills

rills	28.2	6.1	0.55	7.9
no	32.1	5.8	0.52	7.2

(c) concentrated flow

cfl	30.4	6.4	0.54	5
no	31.9	5.7	0.52	5.5

Most of the variations in the relationship between the presence of soil erosion features and per cent of vegetation cover can be explained in terms of land use and the nature of the vegetation cover. Some of these features are found in locations, of different land uses, where the per cent of vegetation cover is high. In the case of wheat and barley areas, vegetation cover is the amount of straw that is left on the soil surface. Most of this cover, however, will be consumed by grazing animals, and what is left will be ploughed in (Plate 8.1). Thus by the beginning of the wet season, such areas are usually bare ground or have only a little cover. It is during this critical time that such features usually develop. In addition, vegetation cover will not be sufficient to protect the soil before the second half of the wet season. Natural vegetation areas that have good cover and where these features are recorded are locations where the vegetation does not form a continuous cover. Therefore, surface runoff can concentrate between vegetation patches leading to the development of such features. In other cases, these features are found on areas of good vegetation cover on lower slopes, while their upper slopes have only poor cover. These are mostly fruit tree areas, where the canopy provides good protection, but this canopy is largely unsuccessful in eliminating runoff once it is initiated from upper slopes.

Plate 8.1
An upper slope area with a good cover of plant residues. However, most of this cover will be consumed by grazing animals before the first rain. Shahhat site.

Table 8.11 Measurement of gullies at each site.

site	total length (metres)	average depth (cm)	average width (cm)
Lussaita	280	65	90
Bayyada	330	110	250
Batta	550	30	35
Magra	365	32.9	62.9
Gobba	-	-	-
Shahhat	245	27.8	51.2

8.4 Conclusion

The results of multiple regression analysis show that despite the complexity of the processes of soil erosion by water, some factors exert most control over the response variables. In addition, these controlling variables have explained, to a certain degree, most of the variations in each response variable.

Infiltration rate, as expected, was mainly influenced by per cent of plant cover. Areas of good cover usually have high organic matter content, improved soil structure, more biological activities, hence, high rates of infiltration. Also topographical factors exert some influence on the infiltration rate. The short steep slopes, although they are generally characterized by shallow soils and their steepness would increase runoff velocity resulting in shorter time for the water to infiltrate into the soil, nevertheless generally have higher rates of infiltration than gentle long slopes. This was mainly because of the factors that directly influence infiltration rate, such as the per cent cover, values of organic matter and the relatively coarse soil materials, all increase on steep short slopes.

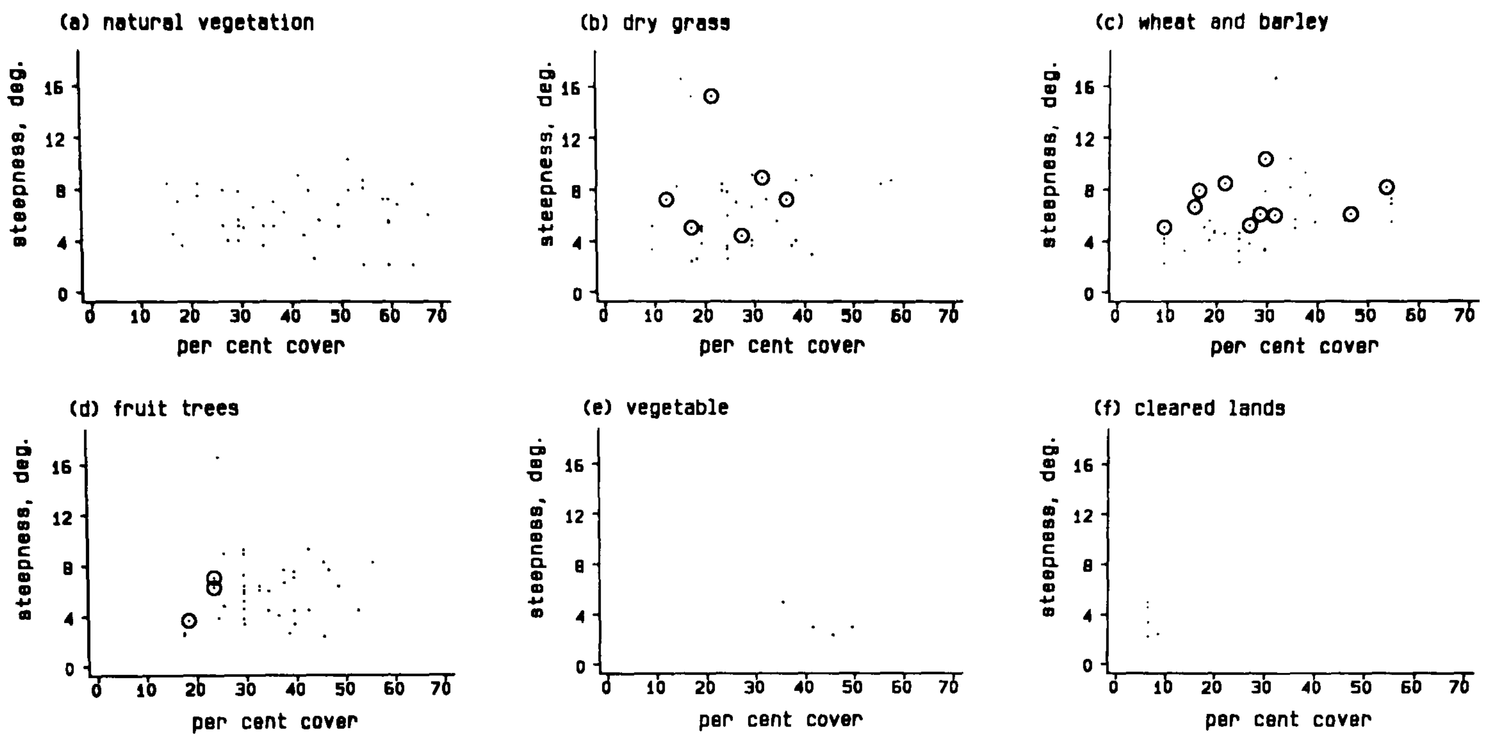
Land topography, namely site and slope angles, showed some influence on per cent of cover. However, it was site angle that exerted the highest influence, i.e., most of the steep parts of the slopes usually have good cover of vegetation. This reflects the degree of vegetation clearing in this area. The only locations that still have good cover of natural vegetation are steep and inaccessible. Even these steep locations are not completely protected, since some of them have poor cover as a result of overgrazing.

Topographical factors of slope steepness, shape and site angle, where runoff velocity and erosivity increases, are the most influential factors on soil depth. The steep slopes, or their steep parts that have convex shapes, usually have shallow soils.

In summary, if steep slopes or their steep parts, although expected to be areas of active erosion, have good cover of vegetation, their organic matter and infiltration rates will be high; therefore, they are less susceptible to water erosion. However, if this cover of vegetation is disturbed or replaced by less protective cover, susceptibility to erosion will be increased even in areas of gentle slopes.

Soil erosion features, particularly gullies and concentrated flow, are usually related to cultivated lower slopes. Here, the soils are relatively deep, fine-textured with low infiltration rates and poor plant cover; the result is more erosive runoff.

A second possibility is that runoff from upper slopes tends to be more concentrated when it emerges onto the cultivated lower slopes. The intensity of these features generally increased on steep slopes that have convex shapes. In addition, the presence of these features was further intensified where roads alter the surface runoff and where the frequency of machine passes is high. In contrast, rills were not related to particular types of land use, but they increase on the steep parts of the slopes, especially where the soils are compacted.



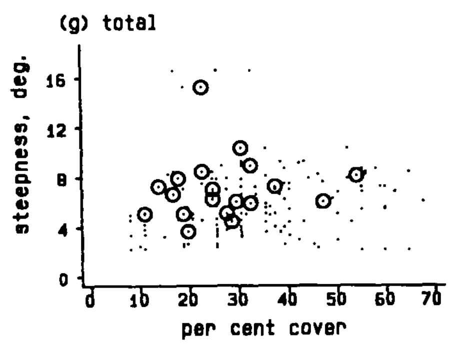


Figure 8.7

Gullying in relation to land use, steepness and per cent cover
(sites with gullies are highlighted)

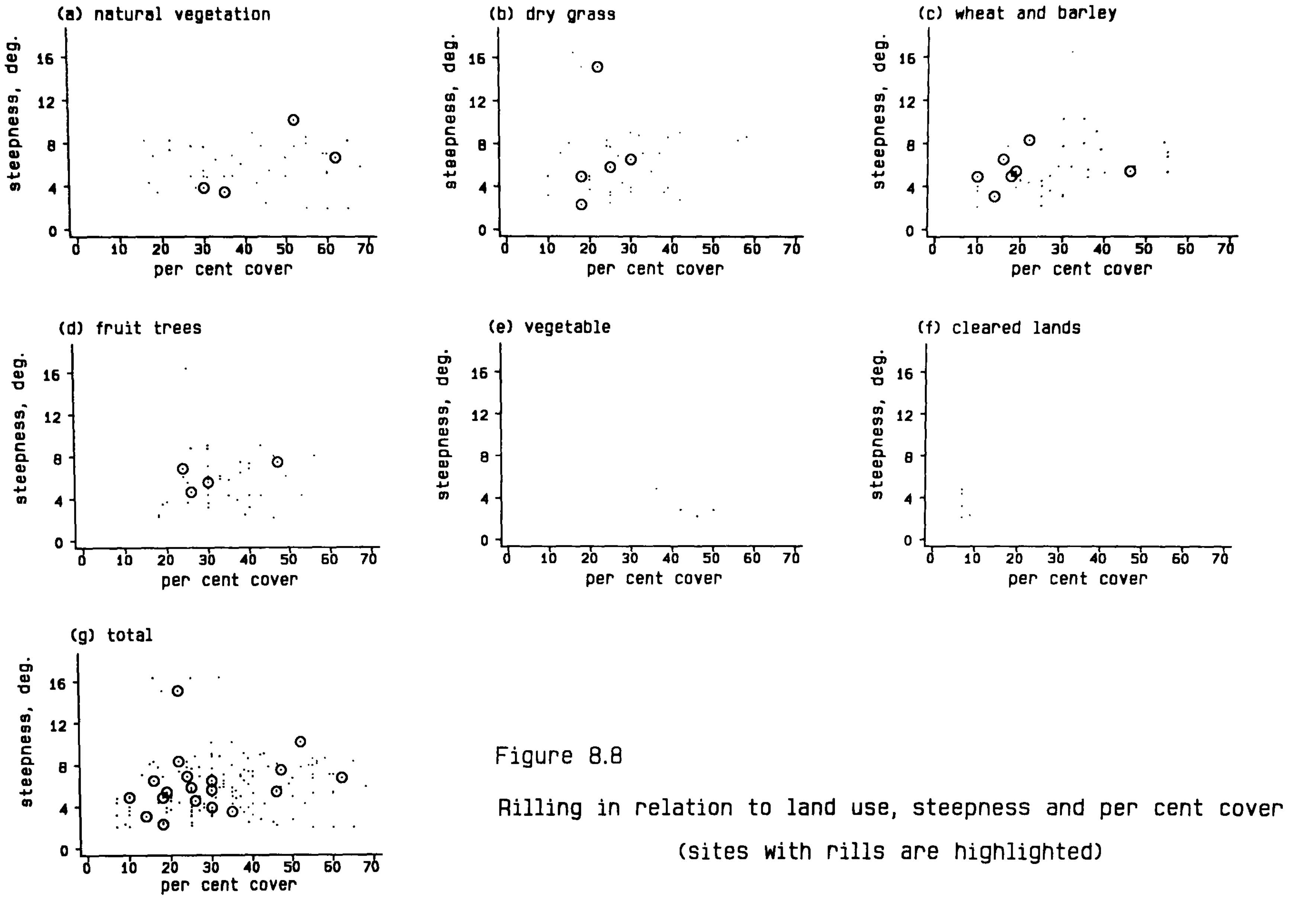
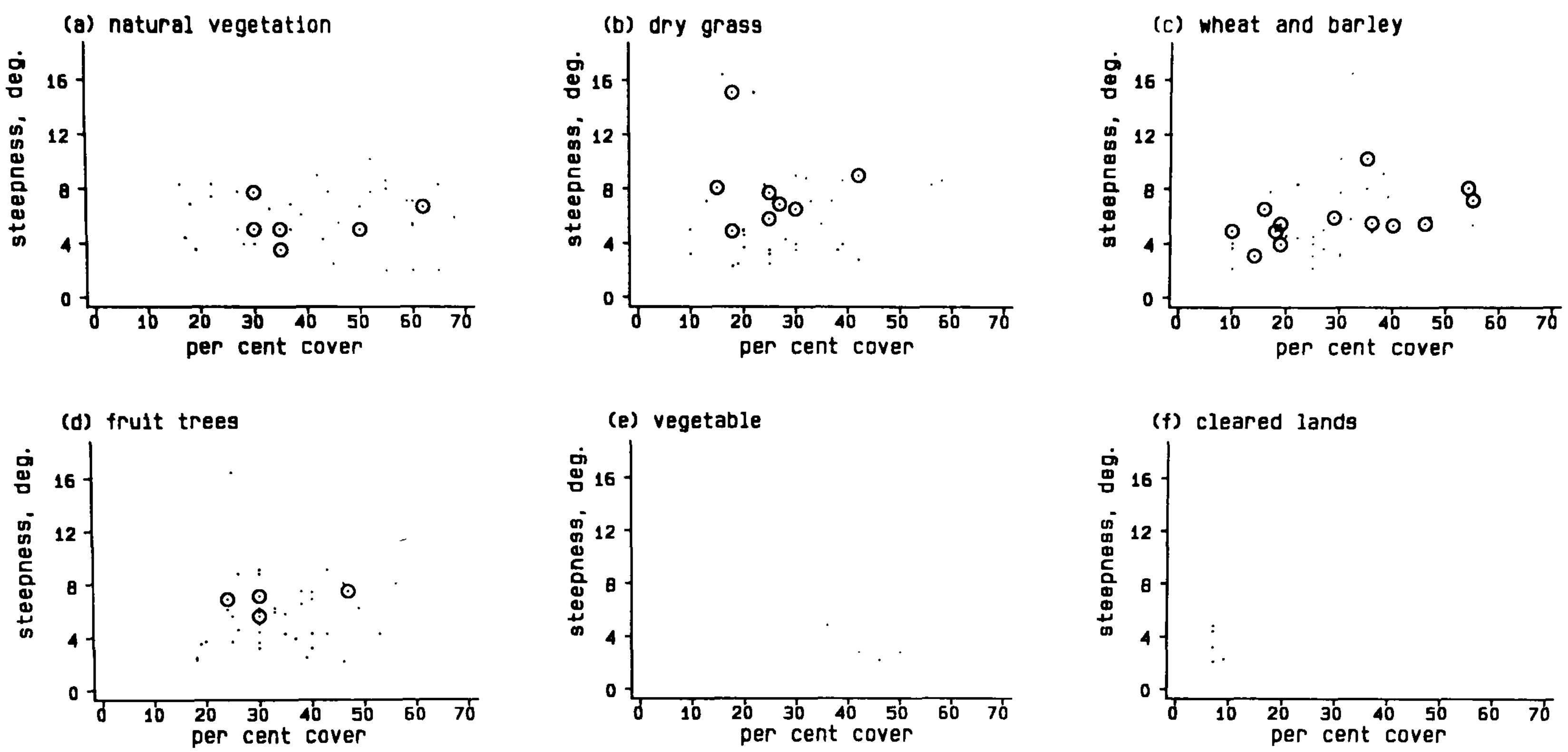


Figure 8.8

Rilling in relation to land use, steepness and per cent cover

(sites with rills are highlighted)



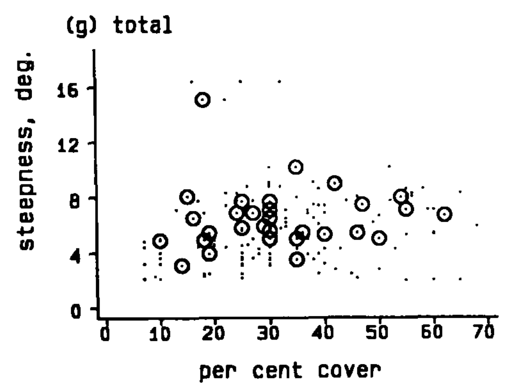


Figure 8.9

Concentrated flow in relation to land use, steepness and per cent cover

(sites with concentrated flow are highlighted)

Chapter 9

Conclusions and recommendations

The focus of this study has been on the importance of soil erosion factors in the process of soil erosion by water on the northern slope of Al-Jabal Al-Akhdar. These factors were assessed in relation to the distribution of erosion features and the rate of soil loss in order to suggest the most suitable measures to prevent or minimize this problem. The area, due to its rainfall characteristics, topography and shallow soils, is susceptible to water erosion. This susceptibility is further increased by the continuous clearing of natural vegetation in order to increase the cultivated area. From the results of this study some conclusions and recommendations can be drawn.

9.1 The importance of the erosion factors

9.1.1 Soil erodibility

From analyzing the soil properties in order to determine soil erodibility some general characteristics of the soils of the study area can be outlined (Table 9.1).

Table 9.1 Summary of frequency of soil texture classes, mean of soil properties and per cent cover.

soil texture fine	soil texture coarse	SD cm	OM %	IR cm hr^{-1}	pcc %
161	31	32.2	2.4	5.3	31.7

fine=silt clay loam and finer coarse=silt loam and coarser
SD=soil depth OM=organic matter IR=infiltration rate
pcc=per cent cover

9.1.1.1 Soil texture

The particle size analysis of 192 soil samples used to determine soil texture classes shows that the soils of the study area are generally fine-textured. Out of the total sample studied 57 were clay (29.7%) and 153 were silty clay loam or finer (78.9%). The highest frequency of clay texture was found at the Magra and Gobba sites. The soils of the former are characterised by compaction, and the latter have vertic characteristics, and the soils of both sites have low infiltration rates and low values of organic matter.

A general pattern of textural distribution is apparent as a result of erosion and deposition down the slope; most of the lower slopes have fine soils, while upper slopes have more coarse soils. Inevitably however, some exceptions occur, whereby lower slopes have more coarse soils. This is usually as a result of steepness, poor vegetation cover or because they terminate in channels. Similarly, some upper slopes have fine soils as a result of relatively higher values of organic matter, small angle, good ground cover or the soils are shallow, and when ploughed the clay-rich subsoil is mixed with the topsoil.

The generally high percentage of clay that the soils of the study area contain should give it some advantages as far as soil erosion by water is concerned. These soils should be coherent and form stable soil aggregates which are resistant to raindrop impact and splash erosion (Evans, 1980). However, these advantages are generally offset by low organic matter content, poor cover and cultivation activities, all of which reduce structural resistance to raindrop impact and hence increase susceptibility to erosion.

9.1.1.2 Infiltration rate

Water infiltration in topsoil showed rates ranging from 0.8 to 15 cm hr^{-1} with an average of 5.3 cm hr^{-1}. In general, the variability depends to a great extent on textural class and organic matter content of the soil, the latter in turn depending on type of land use. In addition, because cracking is one of the characteristics of the soils of the studied sites, infiltration rates are expected to be high, especially at the beginning of the rainy season. On the other hand, the availability of large amounts of loose soil material, during this time, will accelerate the filling-in of these cracks. Furthermore, the tendency of the soils to seal and their low storage capacity will increase the chance of runoff generation even from a small amount of rain. These results suggest that naturally vegetated areas where soils are coarser and organic matter values are higher have higher infiltration rates and hence are only likely to generate low runoff; thus they are less susceptible to water erosion. The lowest rates were recorded at the Magra and Bayyada sites, due to the presence of shallow, compacted, and high clay soils.

9.1.1.3 Organic matter

Values of this soil property were generally low in the study area, particularly in cultivated lands: the average was 2.4%. Although this property was expected to have the same general trend as texture and soil depth, i.e. an increase downslope, it showed a different trend directly affected by neither slope position nor steepness. The main factor influencing this property is land use, areas of natural vegetation usually having higher values of organic matter than cultivated areas. However, some naturally vegetated areas, where grazing is heavy, showed very low organic matter such as the naturally vegetated lower slopes of the Magra site. Also, some cultivated areas, where large amounts of straw are left on the soil surface, recorded relatively high organic matter contents, such as most of the cultivated areas of the Batta site. The full benefit of leaving straw residue is not felt however as by the time of the first rains, most of it will have been consumed by grazing. Therefore, its potentially protective role against raindrop impact and the reduction of runoff velocity is largely eliminated. Thus most of the areas of relatively high organic matter are restricted to the naturally vegetated upper slopes. This aids structural stability and infiltration and hence will reduce runoff generation. This benefit is however limited to some extent by the reduced storage capacity of the shallow soils of these upper slopes.

9.1.1.4 Soil depth

This soil property is very important because soil depth can be used as an indicator of the degree of soil erosion, its susceptibility to erosion and its water storage capacity. Shallow soils usually indicate very active erosion. Soil depth showed a substantial relationship with slope position, i.e., increasing downslope (see chapter 8). Within each slope, soil depth varies according to the slope characteristics, such as local topography, vegetation cover and the angle of each part of the slope. Parts that have rough surfaces, good cover and low angles usually have deeper soils. Most of the upper slopes, because they are active 'natural' erosional areas, have shallow soils. In addition, some of these upper slopes, especially where vegetation is removed, have lost their topsoil. In general, deep soils are mainly found under cultivated areas of gentle lower slopes, while shallow soils are found under naturally vegetated areas located on upper steep slopes.

Thus, apart from soil depth, none of the other soil properties showed a uniformly systematic variation down the slope. However, some soil properties were found to be related to land use and vegetation cover. Both naturally vegetated and some fruit tree areas have relatively high organic matter, coarse soils and high rate of infiltration. On the other hand, those of wheat and barley and dry grass are characterized by low values of organic matter, fine soils and low infiltration rates (see Chapters 6 and 8).

9.1.2 Topography

Topography includes the properties of slope steepness, slope length and slope position. No uniformly systematic relationship between slope steepness, slope length and incidence of erosion was found. However, at some sites erosion features were reported on long or steep slopes, indicating that these two sub-factors have a slight influence on overland flow production (chapter 8).

It is slope position that has the most important apparent influence on both soil properties and the incidence of erosion (Table 9.2). In terms of soil properties, upper slopes generally have shallow, coarse soils, with high organic matter content, high infiltration rates and a good vegetation cover; therefore, soil erosion features were very rare. In contrast, lower slopes have deep fine soils, low organic matter values, low infiltration rates and limited cover; therefore, they recorded the highest frequency of erosion features, especially gullies.

Table 9.2 Mean of soil properties, angles and per cent cover by slope position.

slope position		texture fn.	texture cr.	OM %	IR cm hr^{-1}	pcc %	angle deg.	e.features gl.	e.features cfl	e.features rl.
lower	64	58	6	2.3	5.0	29.1	4.3	17	17	4
middle	64	55	9	2.3	5.4	30.0	5.3	4	10	13
upper	64	48	16	2.8	5.6	35.9	6.5	1	5	3

fn.=fine texture cr.=coarse texture
e.features=erosion features
gl=gullies cfl=concentrated flow rl=rills

9.1.3 Land use and vegetation cover

In general, areas cleared of natural vegetation for cultivation have deep soils and are located on gentle slopes or on the gentler parts of the slope. In contrast those left for natural vegetation are usually of shallow soil and located on the steep parts of the slope or in difficult terrain. The selection of which part of the slope is used for cultivation is mainly based on accessibility and suitability for machine use. However, if the factors of land use and vegetation cover are added, the previous relationship between slope position and soil properties and the incidence of erosion (see section 9.2.2) will be modified as follows. The areas where most of these features are found are cultivated; this is emphasised by the fact that the only case where a gully had formed on an upper slope was at Magra site, in a cultivated area. These lower cultivated slopes are characterized by poor vegetation cover and are unprotected from both raindrop impact and runoff generation during most of the wet season. It is not until the second half of the rainy season that sufficient crop cover develops and rain drop impact and runoff is reduced (Chapter 8). These areas also receive runoff water from adjacent slopes, which, when moving at considerable speed, has an increased erosive potential. The erosivity of runoff, in these areas, is further increased when upper slopes are cleared of vegetation. In this latter case, lower slopes will be affected even when they have good cover of vegetation. At some sites, the development of gullies on cultivated lower slopes was accelerated by the construction of roads and most significantly drains which act to concentrate the surface runoff in a small area.

Table 9.3 Mean of soil properties and per cent cover by land use.

land use	texture fn.	texture cr.	OM %	IR cm hr^{-1}	pcc %	e.features gl.	e.features cfl	e.features rl.	m.loss mm
cultiva.	129	22	1.8	4.7	27.7	21	26	16	3.7
n.veget.	32	9	3.3	6.7	41.7	0	6	4	2.0

m.loss=mean soil loss

To summarize:

1. Areas of natural vegetation and fruit trees are characterized by high organic matter contents, high rates of infiltration

and shallow soils. Although the shallow soils and the erosion pin study (Chapter 7) indicate that erosion does take place from these upper slopes, it is not significant and is not in the form of concentrated flow. As such it can be considered as normal sub-aerial erosion.

2. Areas of seasonal crops, especially wheat and barley, which provide poor ground-cover during the critical time of the rainy season, and are characterized by low organic matter contents and low rates of infiltration, are the most eroded locations. These areas, despite their relatively deep soils and their location in valley floors or on lower parts of the slopes, suffer from the most serious erosion in the sites investigated.
3. Therefore, a general conclusion is that the slope runoff and erosion appear to be more closely related to type of land use than to steepness, length or position of slope.

9.1.4 Rainfall

Although there are spatial variations in the rainfall in the study area, it was assumed that rainfall would be about the same for each site and the only differences within each site would come from the differences in slope properties. It was also expected that an increase of rainfall amount would increase the runoff volume causing an increase in the detachment and transport capacity of the flow and hence an increase in soil loss (Roels, 1984). During the study period a total of 254.1 mm of rain were received at Al-Kouf station, which is about 38.7% less than the 13 year average of this station. The average of surface lowering during this period was 1.8 cm, which is equivalent to 23.4 t ha^{-1} (see chapter 7). This average varies from slope to slope according to the topography, land use and the vegetation cover that characterized each slope. Monthly rainfall, to a certain extent, was related to the monthly soil loss from each slope. The results showed that there is a general increase of the amount of soil loss with the increase of rainfall amount. Most of the variations in the relationship between soil loss and monthly amount of rain, on the four slopes, can be explained by the modification made by slope angle and per cent cover. On the two cultivated slopes, the amount of soil loss for the first few months is a function of the monthly amount of rain and the influence of slope angle. With the advance of the season, when a sufficient plant cover has developed, the effect of these two factors is reduced and the amount of soil loss decreases. The most important aspects in this relationship are:

1. The amount of soil loss is high in the beginning of the rainy season, especially from cultivated slopes, even though their soils are ploughed and infiltration rate can be expected to be high as a result of cultivation. The high amount of soil loss is mainly due to the general absence of vegetation cover and the large amount of available loose material. With weak structures the soil caps very quickly and hence infiltration rates are reduced.
2. The amount of soil loss is reduced, as the crops become established: the development of a relatively good cover, however, takes at least three months.

9.1.5 Erosion factors and incidence of erosion

In the assessment of the distribution of erosion features (gullies, concentrated flow and rills) in relation to topography and land use, it is clear that these features were concentrated on cultivated lower slopes. With the exception of the Magra site, these features were found to decrease upslope. In particular gullies were confined to lower, cultivated slopes, whilst on the vegetated upper slopes only localised areas of concentrated flow were observed at a few locations.

9.1.6 Erosion factors and amount of soil loss

9.1.6.1 Amount of soil loss and topography

Because of the similarity between the slope plots in most of soil properties and slope lengths, the most important factors affecting the rates of soil loss are slope steepness, slope position, land use and vegetation cover.

When the cultivated and naturally vegetated slopes are dealt with separately, the importance of slope angle is reflected in the general increase of soil loss with the increase of slope angle. Furthermore, this relation can be further supported by the influence of site angle. The steep parts of each slope, which are generally the upper parts, are the areas where for a given land use the highest rates of soil loss are recorded. The results also showed that when the cultivated and vegetated slopes are compared, the factor of steepness is strongly influenced by the vegetation cover. The steepest, slope 4, has a lower rate of soil loss than any of the cultivated slopes, as a result of its good vegetation cover (see Table 7.5).

9.1.6.2 Land use and vegetation cover

From the evidence of the erosion pin study at Al-Kouf (see section 7.4), the amount of vegetation cover clearly influences the amount of erosion that takes place. The removal of natural vegetation for the cultivation of wheat and barley ensures that in at least the first three months of the growing season lack of adequate cover results in significantly increased erosion. The naturally vegetated areas are, however, not totally free of erosion; the intensity of rainfall means that even with a ground-cover some erosion is inevitable. Where the vegetation is heavily grazed or has an incomplete cover then considerable erosion can occur.

Combining the results mentioned above, some general statements can be made on the different factors that influence erosion and the distribution of soil erosion features in the study area. The most important factor is the removal of natural vegetation from the lower slopes to enable the land to be used for cereal cultivation. This ensures a major increase in erosion as the most intensive rainfall is concentrated in the earliest months of the growing season when the soils have very little protection from the growing crop. Replacement of natural vegetation with fruit trees on the other hand has little effect on erosion rates.

9.2 Recommendations

The results of this study show that the incidence and rates of soil erosion are serious in the study area. Cultivated lands, where the soils have to be left bare for part of the wet season, are the most affected and the most prone to erosion. Of the several factors studied that contribute to this accelerated erosion, land use and vegetation cover are the most important. These factors, in addition to their direct influence on the erosion incidence and amount of soil loss, also influence other factors, such as rainfall erosivity and certain soil properties. Therefore, the maintenance of a good vegetation cover is an important step toward solving this problem. It also appears that runoff generation and its erosivity is the most important erosion agent. Thus, reducing the chance for runoff generation or minimizing its erosivity when generated is another important step to reduce soil erosion. Most of the recommendations for soil conservation will be based on maintaining a good cover of vegetation, increasing infiltration capacity of the soil, improving its aggregate stability and increasing the surface roughness. These can be achieved mainly by adopting measures that can improve land use and soil management, supported by simple physical methods. In addition, most of the recommended measures have been found effective in similar environments in minimizing soil erosion and improving soil quality.

Although there is an overlap between the different conservation methods, it is considered appropriate to divide these methods into two groups. These groups are physical measures and farming practice. However, in order to control the erosion problem these two methods should work together, because none of these methods alone can be expected to solve the erosion problem.

9.2.1 Physical measures

1. During the field study, it was observed that in the locations where the Roman check-dams were still in good condition, soils were usually deep and there was no sign of soil erosion. Therefore, maintaining existing Roman check-dams, and building new ones where appropriate, is very important. Check-dam construction in water-ways has proved to be effective in reducing the rate of bank erosion and the enlargement of gullies developed on valley floors (Bensalem, 1977).

2. On the steep slopes, where tractors can only operate up and down the slope, and only poor crops of wheat and barley can be grown on the shallow soils, land use has to be changed to a more stable form of land use. The solution introduced by FAO, in a similar dryland farming area of Jordan, was to build stone walls on the contour, inter-planted with perennial crops such as fruit trees. These walls slowed runoff, increased infiltration, trapped soil materials and gradually built bench terraces (Sanders 1988). The technique of constructing small walls of loose stones was also recommended in the North African countries of Tunisia, Algeria and Morocco. As the depth of silt deposit rises, new stones are added to raise the height of the wall, which ultimately leads to the formation of a level terrace (Bensalem, 1977). A further advantage of this approach is that these stonewall terraces are well known in the region, and once they are constructed require little maintenance. Also because stones

are the main material required for their construction, and are usually available within the farm, construction of these walls is not expected to be costly. However, with the use of terraces, there is a risk of terrace failure during unusual events of heavy rains. This can cause a sudden release of the water accumulated up on the hillside, resulting in a very severe damage (Morgan, 1986 and Rapp et al., 1972). Therefore, terraces, especially those constructed in the central part of the study area, where the amount of rain is high, should be supported by overflow channels to deal with excess water.

3. Gullies were mainly found on cultivated valley floors. These lands, in addition to their poor plant cover and the little protection it provides, collect more water from adjacent upslope areas, which makes the runoff more erosive. The gullies are also enlarged where construction of a road alters surface runoff by concentrating in a small area via pipes and drains. The largest gullies in the study area were associated with such roads. Thus, protective measures such as the construction of roads to follow the topography are recommended. These gullies also can be reclaimed by constructing a series of composite earth and stone check-dams on the gully bed. The area around the gully as well as gully heads and sides can be stabilized by planting suitable tree and grass species.

To reclaim and control gully erosion, small dams can be built across gullies to trap sediment and reduce gully enlargement. The dams are usually made from locally available materials such as earth or loose rocks. These structures, as well as agronomic treatment of the surrounding land where a good vegetation cover is planted, should work together to stabilize gullies. Construction details can be found in the published literature of soil conservation (e.g. Finkel, 1986 and Morgan, 1986). However, Finkel (1986), in his study of soil and water conservation in semiarid areas, suggested some measures to control gully erosion in environments that are similar to the northern slope of Al-Jabal Al-Akhdar. According to Finkel, the control of the U-shaped gullies, like those found in the studied sites, should be concentrated on the sidewalls and the headwalls, where erosion is active. Therefore, the methods employed should follow these steps.

1. A series of dams should be constructed along the gully. The lowest dam should be lower than the one above it, and all should be lower than the surrounding land. Also these dams could be constructed to be either low and closely spaced or high and apart from each other.
2. The reshaping of the vertical sidewalls to a sloping bank. This will prevent the sidewalls from being undermined by the flow in the bottom of the channel or by water entering from the sides.
3. The third step is the channel stabilizing by vegetation planting. Vines, woody shrubs and trees such as carob all can form a good bank cover for large gullies. However, it is very important that livestock is excluded from the gullied areas so vegetation is able to provide protective cover.

9.2.2 Farming practice

Contour ploughing was found to be effective in reducing soil erosion by water in the North African countries (Bensalem 1977). This involves the ploughing of a deep furrow every 30-40 m along the contour; these furrows intercept runoff and control its removal from the land, and they also reduce saturation which may encourage landsliding. In addition to this method, mulching is also recommended. This technique involves leaving a sufficient amount of crop residue on the surface after harvesting or the addition of extra organic material at the surface. For planting this is only shallow cultivated to maintain cover. Mulching provides protection from raindrop impact, maintains infiltration and promotes soil roughness, and over time will raise the organic matter status, and hence structural stability. In addition, a good cover of plant residues simulates the effect of a plant cover. It is most useful as an alternative to cover crops in areas where the absence of rain prevents the establishment of a ground cover before the beginning of the wet season, such as the study area. For such areas, further benefits of mulch are the reduction of soil temperature and evaporation, hence conserving its moisture content (Morgan, 1986). However, the efficiency of this technique is reduced by the practice of stubble grazing (Bensalem, 1977). A second option is to use organic manures wherever possible. This adds both organic matter and nutrients, thus improving the physical and chemical status of the soils. Mwendera and Feyen (1993) recommend pre-rain ploughing to increase both infiltration and surface roughness, hence, at first, at least reducing runoff. The high intensity rainfall and low organic matter content will probably lead to surface smoothing, cap formation and hence increased runoff. This approach has therefore little to recommend it in preference to surface mulching. In addition to decreasing erosion, this method will increase soil productivity (Halloran, 1993). However, because when the residues are buried in the ground their decomposition will temporarily tie up the available nitrogen to the detriment of the new seedlings, an application of nitrogen fertilizer is required (Finkel, 1986).

Steep slopes, especially their upper parts, should be kept as areas of natural vegetation, where no clearing or heavy grazing should be allowed. At the studied sites, some of the upper slopes were so affected by heavy grazing that tree branches close to the surface as well as the litter layer of the surface were reduced. In such areas, closure to grazing to allow natural revegetation is recommended. It has been also found that at the studied sites, the good vegetation cover of lower slopes could not protect these areas against runoff that was generated on upper poorly vegetated slopes. Therefore, on the upper slopes, where soils are usually unsuited for agricultural production, the establishment of vegetation cover is one of the best soil and water conservation measures. In addition, a conservation program of planting trees in the headwater catchments should be adopted, to help reduce soil erosion and control flooding. Here, *Pinus halpensis,* which is a tree that is well adapted to the poor water and nutrient resources available on the drier and rocky slopes, is recommended (Finkel, 1986).

Only machines of light weight should be used, operated by people of some experience, in both land clearing and cultivating. Also, in order to reduce machines' degrading influence, the number of passes as well as the weight of the different kinds of equipment should be limited.

In addition to the fact that both physical and improved farming methods should work together in order to achieve good results, it is also important to gain farmer acceptance and participation in any conservation project. From the results of different studies and the experience of other countries, this can be achieved by adopting the following:

1. The farmers must understand the economic, environmental, and social consequences of their actions. In addition, conservation must be associated with clear productivity benefits to the farmers themselves.
2. The causes and consequences of erosion should be explained to the farmers so that they understand the reasons for conservation, and the necessity of long-term maintenance.
3. It is also important to consider other factors such as a social study and environmental impact analysis. The social study is necessary to ensure that any recommendations meet the needs and have the approval of the local community. The environmental impact study is to ensure that on-site degradation has been thoroughly covered, and to investigate the off-site effects.

Finally, more research is needed to relate soil loss to productivity loss, and also to make an economic analysis in terms of costs and benefits of any conservation project. It is difficult to determine stocking rates, and carrying capacity of grazing areas, especially where the annual rainfall variability is high. However, studies of this type, or even rough estimates of the carrying capacity of grazing areas and the number of grazing animals, are needed. This will help to determine the suitable stocking rates which will lead to the maintenance of vegetative cover.

9.3 Further research

A cosequence of the research presented here is the identification of future lines of enquiry. Areas particularly waranting further study are as follows.

1. Seting up plots and measurements of soil and water losses on a storm basis to determine the average annual soil loss.
2. An examination of the sedimentry sequence found in valley fills or accumulated behind the Roman check dams. This accumulation of sediment can be dated using different techniques (see Chapter 7) will allow comparisons to be made between present and historical rates of erosion.
3. Carry out a detailed study to determine the structural stability of the soil on different slopes and on different land use, so it can be related to organic matter content infiltration rates and erosion dynamics.

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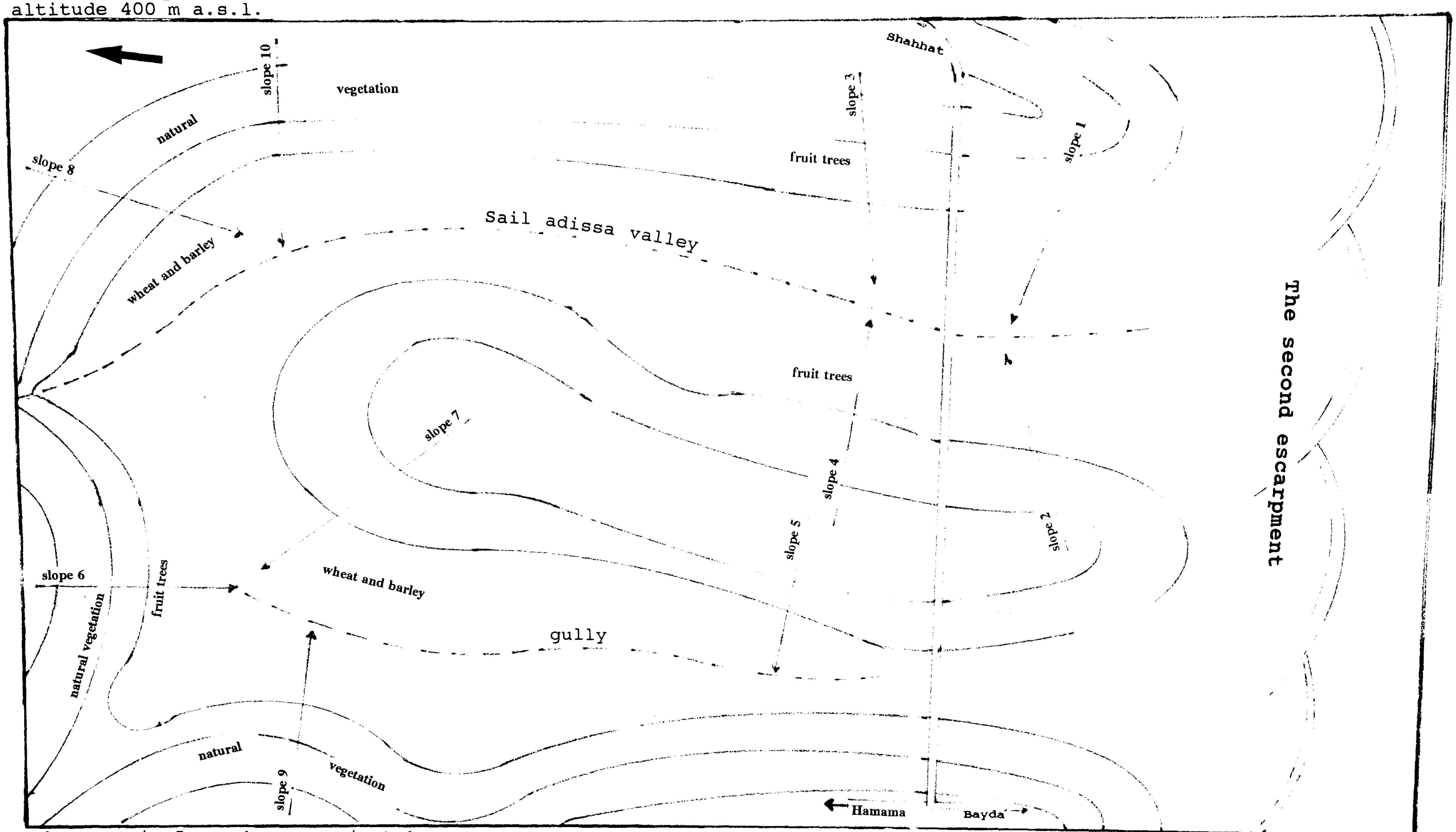
Appendix 1. Slope profile and cross-profile survey

A sketch map of lussaita site

altitude 400 m a.s.l.



(The area is 5 sq. km approximately)

2. Slope profile survey

slope no.	bearing (deg)	length (m)	steepness (deg)	soil type	channel width(m)
1	270	314	9.0	ferric red	4
2	90	547	7.7	ferric red	4
3	270	382	6.2	ferric red	2
4	100	337	4.3	ferric red	2
5	260	253	7.8	ferric red	0
6	180	367	8.1	ferric red	0
7	290	238	4.9	ferric red	0
8	190	290	6.9	ferric red	2
9	90	289	5.0	ferric red	1
10	270	308	7.8	ferric red	2.5

3. Cross-profile survey

a. Vegetation cover, stones and land use type.

pno	cpno	dsp	trs	shb	stn	oce	w/b	drgr	land use
1	lower	27	0	0	3	0	0	8	dry grass
1	middle	81	0	0	7	0	0	7	dry grass
1	upper	236	4	8	5	0	0	0	n.vegetation
2	lower	46	3	0	6	0	4	4	wheat/barley
2	middle	125	1	0	8	2	0	5	dry grass
2	upper	413	2	4	6	0	0	6	n.vegetation
3	lower	86	3	0	1	0	0	5	fruit trees
3	middle	212	4	0	5	0	0	0	fruit trees
3	upper	303	2	0	2	0	0	0	fruit trees
4	lower	48	0	5	4	0	0	7	n.vegetation
4	middle	142	4	0	4	0	0	0	fruit trees
4	upper	280	2	0	4	0	0	0	fruit trees
5	lower	15	0	0	2	0	5	0	wheat/barley
5	middle	86	3	4	7	1	0	1	n.vegetation
5	upper	223	0	1	2	1	0	5	n.vegetation
6	lower	12	0	0	3	0	0	4	dry grass
6	middle	108	3	0	0	0	0	4	fruit trees
6	upper	284	3	0	2	0	0	3	fruit trees
7	lower	23	0	0	5	0	0	5	dry grass
7	middle	64	0	0	5	0	0	5	dry grass
7	upper	124	5	5	0	3	0	2	n.vegetation
8	lower	57	0	0	5	0	0	4	dry grass
8	middle	142	0	0	3	0	0	5	dry grass
8	upper	206	3	5	4	3	0	2	n.vegetation
9	lower	27	0	0	3	0	10	0	wheat/barley
9	middle	123	2	0	4	0	2	0	n.vegetation
9	upper	196	3	8	2	4	0	2	n.vegetation
10	lower	56	0	2	5	0	0	2	dry grass
10	middle	123	0	6	5	0	0	5	dry grass
10	upper	214	6	5	2	3	0	4	n.vegetation

pno=slope profile number cpno=cross-profile number
dsp=distance of cpno from the startingpoint(m)
trs=trees shb=shrubs stn=stones oce=outcrop exposed
w/b=wheat and barley dgr=dry grass

b. Soil properties

pno	cpno	soil texture	ir	om	oc	sd
1	lower	clay loam	5.0	2.5	1.25	26.8
1	middle	silt loam	9.0	3.2	1.59	20
1	upper	silt loam	7.0	3.6	1.8	19.8
2	lower	clay loam	4.0	3.8	1.88	10.6
2	middle	clay loam	9.0	2.4	1.2	14
2	upper	silt loam	10.0	3.0	1.5	19
3	lower	silt clay loam	8.0	1.9	.96	20
3	middle	clay loam	6.0	1.8	.92	26.6
3	upper	silt clay loam	7.2	2.2	1.08	24
4	lower	clay	8.0	2.2	1.11	35
4	middle	silt clay	9.0	2.3	1.13	27
4	upper	silt clay loam	9.0	2.6	1.28	31.2
5	lower	clay	9.0	0.9	.46	36.6
5	middle	silt clay loam	7.0	1.4	.69	8.8
5	upper	silt clay loam	3.2	3.4	1.7	23.2
6	lower	clay	9.6	1.3	.63	57.2
6	middle	clay	9.9	2.0	1.01	36.8
6	upper	clay	.	3.2	1.59	43.6
7	lower	clay	9.6	1.4	.71	47
7	middle	clay	3.6	1.4	.69	49
7	upper	silt clay	.	3.5	1.73	22.4
8	lower	clay	3.0	1.8	.92	30
8	middle	clay	4.2	1.3	.64	34.8
8	upper	loam	.	2.6	1.29	19.4
9	lower	clay	3.6	1.4	.68	47.6
9	middle	clay	4.2	1.5	.77	38.2
9	upper	silt loam	.	3.1	1.55	8.6
10	lower	silt clay loam	3.0	1.9	.95	24.8
10	middle	silt clay	4.2	1.5	.76	26
10	upper	clay	.	3.8	1.9	20.4

ir=infiltration rate (cm hr^{-1}) om=organic matter (%)
oc=organic carbon (%) sd=soil depth (cm)

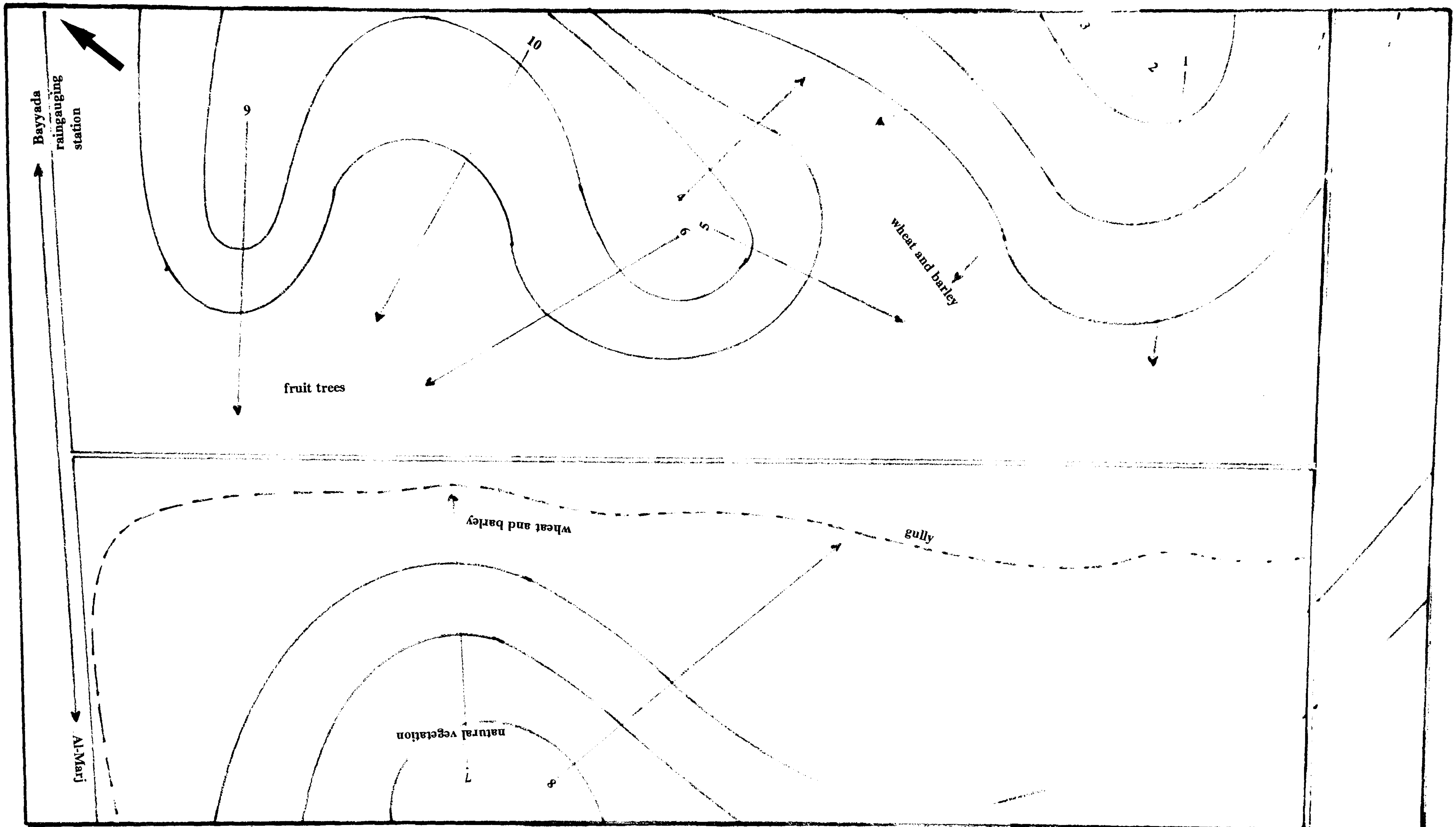
c. Soil surface characteristics

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	yes	yes	no	no	no	no
1	middle	no	no	no	no	no	no
1	upper	no	no	no	no	yes	no
2	lower	no	no	no	no	no	no
2	middle	no	yes	no	no	no	no
2	upper	yes	yes	no	no	no	no
3	lower	no	no	no	no	no	no
3	upper	no	no	no	no	no	no
3	middle	no	no	no	no	no	no
4	lower	yes	yes	yes	no	no	no
4	middle	no	no	yes	yes	no	no
4	upper	no	no	yes	no	no	no
5	lower	no	no	no	yes	no	no
5	middle	no	no	no	no	no	yes
5	upper	no	no	no	no	no	no
6	lower	no	few	yes	no	no	no
6	middle	no	no	yes	no	no	no
6	upper	no	few	yes	yes	no	no
7	lower	no	few	no	no	no	no
7	middle	no	few	no	no	no	no
7	upper	no	few	no	no	no	yes
8	lower	no	few	no	yes	no	no
8	middle	yes	few	no	no	no	no
8	upper	yes	no	no	no	no	no
9	lower	no	few	no	no	no	no
9	middle	yes	no	no	yes	no	no
9	upper	yes	no	yes	no	no	no
10	lower	no	no	no	no	no	no
10	middle	no	few	no	yes	no	no
10	upper	no	no	no	no	no	no

surfcrus=surface crust compact=compaction
farmprac=farming practice biolact=biological activities
ert=exposed roots

A sketch map of Bayyada site

altitude 400 m a.s.l.



(The area is 5 sq. km approximately)

2. Slope profile survey

slope no.	bearing (deg)	length (m)	steepness (deg)	soil type	channel width (m)
1	200	412	5.4	f.r.comp	0
2	250	410	3.9	f.r.comp	0
3	270	399	3.1	f.r.comp	0
4	90	410	2.1	f.r.comp	0
5	170	314	4.0	f.r.comp	2.5
6	270	453	6.1	f.r.comp	3.5
7	60	353	6.5	f.r.comp	2.5
8	90	434	2.5	f.r.comp	0
9	210	624	2.3	f.r.comp	0
10	230	308	2.5	f.r.comp	0

f.r.comp=ferric red compacted soil

3. Cross-profile survey

a. Vegetation cover, stones and land use

pno	cpno	dsp	trs	shb	sts	ocn	w/b	drgr	land use
1	lower	20	0	0	5	0	6	0	wheat/barley
1	middle	96	0	0	13	0	5	0	wheat/barley
1	upper	231	0	0	9	0	0	5	dry grass
2	lower	18	0	0	3	0	6	0	wheat/barley
2	middle	123	2	8	9	0	0	0	n.vegetation
2	upper	222	0	0	10	0	0	3	dry grass
3	lower	50	0	0	2	0	5	0	wheat/barley
3	upper	229	0	0	10	0	5	0	wheat/barley
3	middle	100	0	0	3	0	6	0	wheat/barley
4	lower	80	0	0	3	0	5	0	wheat/barley
4	middle	200	0	0	5	0	0	4	cleared
4	upper	305	0	0	11	0	0	3	cleared
5	lower	19	0	0	1	0	6	0	wheat/barley
5	middle	81	0	0	2	0	4	2	wheat/barley
5	upper	190	1	0	10	0	3	0	wheat/barley
6	lower	20	2	0	2	0	0	6	fruit trees
6	middle	93	2	0	3	0	0	10	fruit trees
6	upper	283	1	0	3	2	0	8	n.vegetation
7	lower	36	0	0	2	0	3	4	wheat/barley
7	middle	101	0	0	11	0	4	2	wheat/barley
7	upper	192	0	0	4	3	3	0	n.vegetation
8	lower	45	0	0	0	0	0	12	dry grass
8	middle	190	1	0	1	0	0	14	fruit trees
8	upper	343	1	0	13	0	0	4	dry grass
9	lower	34	4	0	2	0	0	12	fruit trees
9	middle	210	4	0	0	0	0	14	dry grass
9	upper	446	0	0	17	0	0	0	cleared
10	lower	65	4	0	2	0	0	12	fruit trees
10	middle	165	3	0	1	0	0	13	fruit trees
10	upper	235	0	0	15	2	0	3	n.vegetation

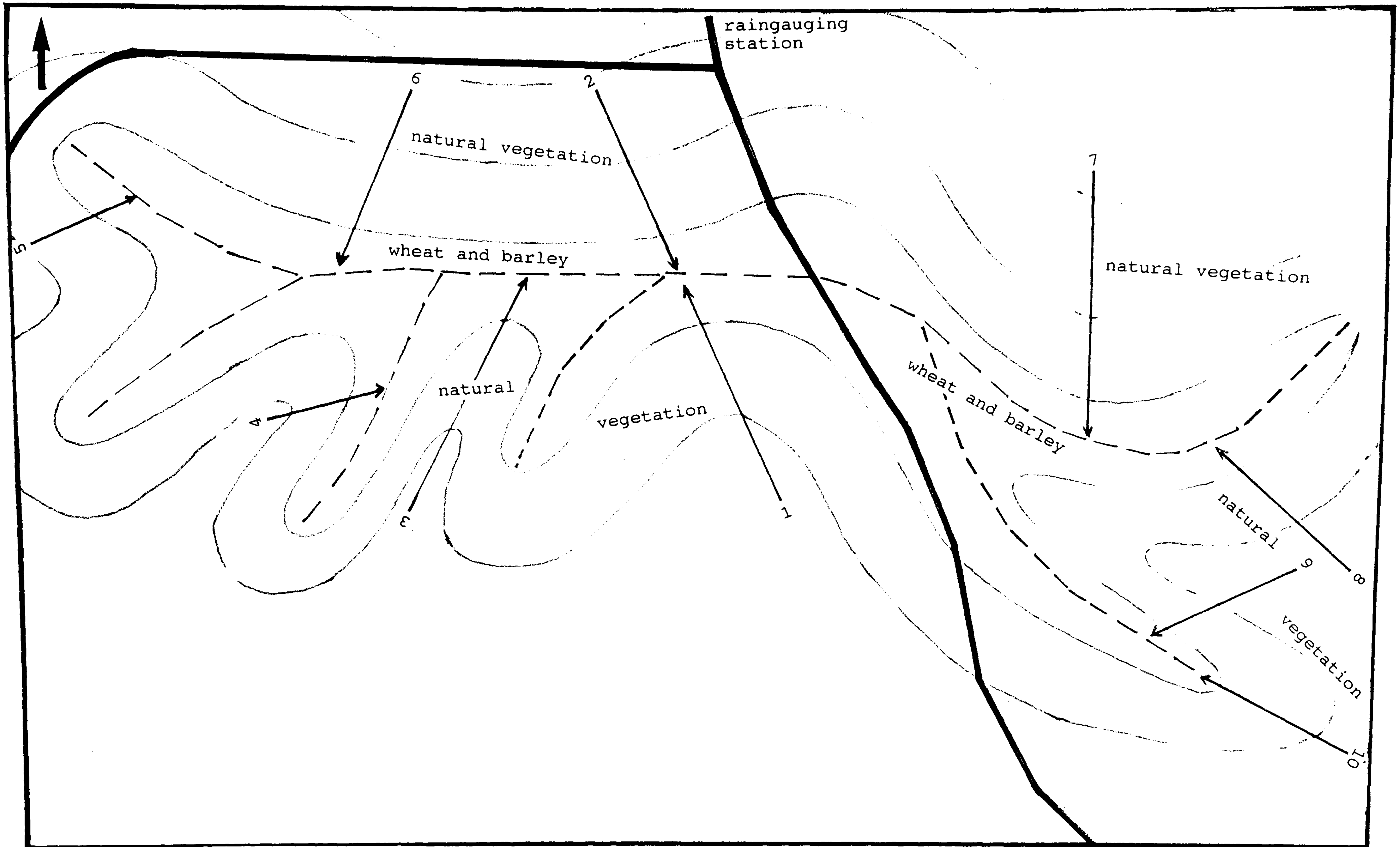
b. Soil properties

pno	cpno	soil texture	ir	om	oc	sd
1	lower	silt loam	2.8	1.3	.66	31
1	middle	silt loam	3.0	1.0	.51	54
1	upper	silt clay loam	3.9	2.2	1.1	30.2
2	lower	silt clay loam	2.8	1.2	.62	41.6
2	middle	clay loam	3.0	2.6	1.28	22.6
2	upper	loaml	3.9	2.6	1.26	32
3	lower	silt clay loam	2.6	1.8	1.5	36.6
3	middle	loam	3.0	2.9	1.43	44
3	upper	clay loam	3.0	1.6	.8	41
4	lower	silt clay loam	3.6	1.4	.67	43
4	middle	silt clay loam	4.0	1.4	.68	30.4
4	upper	clay loam	2.8	1.7	1.36	35.2
5	lower	silt clay loam	2.8	1.0	.48	34.4
5	middle	silt clay loam	4.0	1.2	.6	40.2
5	upper	clay loam	2.8	3.0	1.51	21
6	lower	silt loam	1.2	1.7	.85	23.6
6	middle	loam	3.6	1.7	.83	12
6	upper	silt clay loam	5.4	3.8	1.9	21.2
7	lower	silt clay loam	1.2	1.8	.9	26
7	middle	loaml	3.6	2.3	1.14	27.8
7	upper	clay loam	5.4	3.1	1.56	31.6
8	lower	silt clay loam	0.8	1.9	.94	34.4
8	middle	silt loam	3.8	4.8	.83	43
8	upper	loaml	3.6	1.7	2.39	23
9	lower	silt clay loam	0.8	1.6	.8	43.4
9	middle	silt clay loam	3.8	1.5	.75	47.4
9	upper	silt loam	3.6	0.4	.22	18.8
10	lower	silt clay loam	0.8	1.7	.85	55.4
10	middle	silt clay loam	3.8	1.5	.77	42
10	upper	loam	3.4	4.7	2.34	9.2

c. Soil surface characteristics

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	no	no	yes	no	no	no
1	middle	no	no	yes	yes	no	yes
1	upper	no	no	no	no	yes	no
2	lower	no	no	yes	no	no	no
2	middle	no	no	no	no	no	yes
2	upper	no	no	no	no	no	no
3	lower	no	no	no	no	no	no
3	middle	no	no	no	no	no	no
3	upper	no	no	no	no	yes	no
4	lower	no	no	no	no	no	no
4	middle	no	no	yes	yes	no	no
4	upper	no	no	no	yes	no	no
5	lower	no	no	no	no	no	no
5	middle	no	no	no	no	no	no
5	upper	no	no	no	no	yes	no
6	lower	no	no	no	yes	no	no
6	middle	no	no	yes	yes	no	no
6	upper	yes	no	no	no	no	no
7	lower	yes	yes	yes	no	no	no
7	middle	yes	yes	no	no	no	no
7	upper	yes	no	no	no	no	yes
8	lower	yes	yes	no	no	no	no
8	middle	yes	yes	no	no	no	no
8	upper	no	no	no	no	yes	no
9	lower	yes	yes	yes	no	no	no
9	middle	yes	yes	no	no	no	no
9	upper	no	no	no	no	no	no
10	lower	yes	yes	yes	no	no	no
10	middle	no	yes	no	no	no	no
10	upper	yes	no	no	no	no	no

A sketch map of Batta site
altitude 340 m a.s.l.



(The area is 6 sq. km approximately)

2. Slope profile survey

slope no.	bearing (deg)	length (m)	steepness (deg)	soil type	channel width (m)
1	300	226	10.2	ferribrn	2
2	120	264	6.7	ferribrn	2
3	10	274	8.0	ferribrn	1.2
4	90	294	5.4	ferribrn	.5
5	20	237	5.9	ferribrn	.5
6	230	231	5.5	ferribrn	.5
7	180	475	7.1	ferribrn	2.5
8	290	366	5.3	ferribrn	2.5
9	240	254	8.6	ferribrn	0
10	280	268	8.3	ferribrn	0

ferribrn=ferric brown soil

3. Cross-profile survey

a. Vegetation cover, stones and land use type

pno	cpno	dsp	trs	shb	stn	oce	w/b	drgr	land use
1	lower	22	0	0	3	0	4	0	wheat/barley
1	middle	59	0	16	2	0	0	0	n.vegetation
1	upper	118	0	0	7	0	4	0	wheat/barley
2	lower	12	0	0	3	0	5	0	wheat/barley
2	middle	46	1	0	3	0	4	0	n.vegetation
2	upper	190	0	0	6	0	5	0	n.vegetation
3	lower	11	0	0	5	0	4	0	wheat/barley
3	middle	28	0	0	5	0	4	0	wheat/barley
3	upper	83	0	10	3	4	0	0	n.vegetation
4	lower	15	0	0	1	0	5	3	wheat/barley
4	middle	71	0	0	4	0	2	5	wheat/barley
4	upper	172	0	9	3	2	0	6	n.vegetation
5	lower	10	0	0	5	0	4	0	wheat/barley
5	middle	27	0	0	6	0	4	0	wheat/barley
5	upper	90	3	12	3	0	0	0	n.vegetation
6	lower	10	0	0	5	0	3	0	wheat/barley
6	middle	55	0	1	6	0	0	4	n.vegetation
6	upper	98	0	0	9	0	0	9	n.vegetation
7	lower	22	0	0	7	0	3	5	wheat/barley
7	middle	74	1	3	9	0	0	4	n.vegetation
7	upper	134	2	6	3	0	0	0	n.vegetation
8	lower	16	0	0	5	0	3	4	wheat/barley
8	middle	54	0	0	5	0	2	4	wheat/barley
8	upper	269	3	14	2	0	0	0	n.vegetation
9	lower	15	0	0	7	0	0	4	dry grass
9	middle	57	0	0	2	0	0	4	dry grass
9	upper	158	0	16	4	0	0	0	n.vegetation
10	lower	22	0	0	7	0	0	5	dry grass
10	middle	53	0	0	4	0	0	2	dry grass
10	upper	194	0	18	1	0	0	0	n.vegetation

b. Soil properties

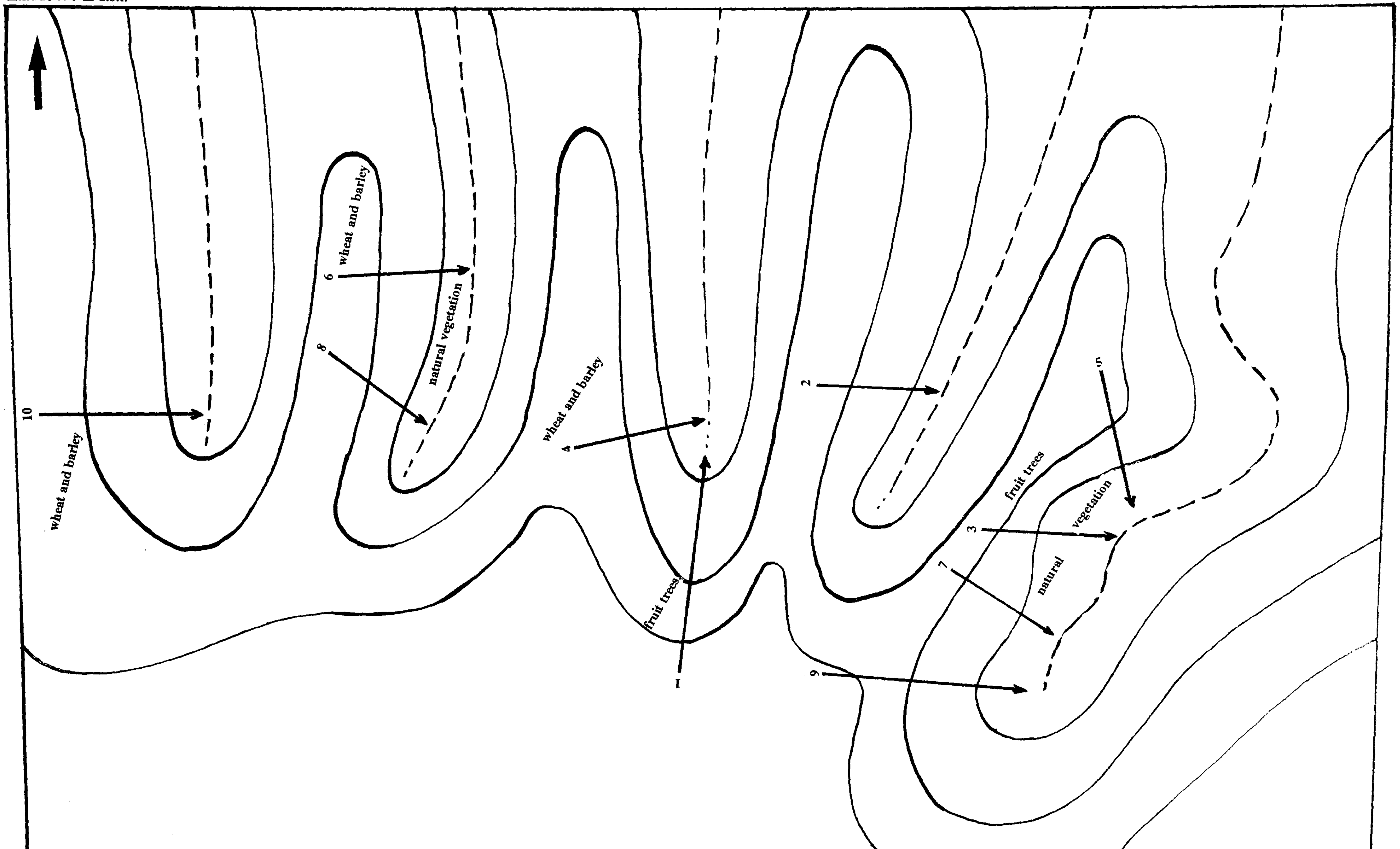
pno	cpno	soil texture	ir	om	oc	sd
1	lower	silt clay loam	8.8	1.8	2.08	47
1	middle	clay loam	7.2	4.2	.9	31.5
1	upper	clay loam	11.7	2.6	2.3	23
2	lower	silt clay loam	8.8	5.0	2.48	35.6
2	middle	silt clay loam	7.2	5.1	2.56	31
2	upper	loam	12.0	4.1	2.07	36.4
3	lower	silt clay loam	8.8	5.0	2.51	60
3	middle	clay loam	7.2	1.5	.76	48.4
3	upper	silt clay loam	8.8	4.3	2.13	31
4	lower	silt clay loam	6.0	4.4	2.19	46.4
4	middle	silt clay loam	7.2	4.4	2.21	41.8
4	upper	silt clay loam	8.8	5.5	2.75	36.2
5	lower	silt clay loam	6.0	4.4	2.2	31.6
5	middle	clay loam	7.2	4.7	2.33	29.2
5	upper	silt loam	8.8	5.7	2.84	29
6	lower	silt clay loam	6.0	2.7	2.42	36.2
6	middle	silt clay loam	7.2	2.1	1.03	21
6	upper	loam	12.0	3.0	1.49	38.2
7	lower	silt clay loam	7.0	4.8	2.4	36
7	middle	clay loam	7.2	5.0	2.5	33.8
7	upper	silt clay loam	2.8	4.2	1.26	45.6
8	lower	silt clay loam	7.2	2.7	2.09	32
8	middle	silt clay loam	7.2	4.2	2.12	27.8
8	upper	clay loam	.	5.4	2.7	25
9	lower	clay loam	6.0	3.0	1.48	13
9	middle	silt clay loam	7.0	4.4	2.22	27.4
9	upper	clay loam	.	3.8	.87	25.4
10	lower	clay loam	6.0	3.9	1.97	13
10	middle	sandy loam	7.0	1.5	.77	13.6
10	upper	silt clay loam	.	5.6	2.81	28.2

c. **Soil surface characteristics**

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	no	no	no	no	no	no
1	middle	no	no	no	yes	no	no
1	upper	no	yes	no	no	no	no
2	lower	no	no	no	no	no	no
2	middle	no	no	no	no	no	no
2	upper	no	yes	no	no	yes	no
3	lower	no	no	no	no	yes	no
3	middle	no	no	no	no	no	no
3	upper	no	no	no	no	no	no
4	lower	no	no	no	no	no	no
4	middle	yes	yes	no	no	no	no
4	upper	yes	no	no	no	no	no
5	lower	no	no	no	no	no	no
5	middle	no	yes	no	no	no	yes
5	upper	no	no	no	no	yes	no
6	lower	no	no	no	no	yes	no
6	middle	no	no	no	yes	no	no
6	upper	no	no	no	yes	no	no
7	lower	yes	no	yes	no	yes	no
7	middle	yes	yes	no	no	yes	yes
7	upper	yes	no	no	no	no	no
8	lower	yes	no	no	no	no	no
8	middle	no	yes	no	yes	no	yes
8	upper	yes	no	no	no	no	no
9	lower	no	no	yes	no	no	no
9	middle	no	yes	no	no	yes	no
9	upper	no	no	no	no	no	no
10	lower	no	no	yes	no	no	no
10	middle	no	no	no	no	no	no
10	upper	yes	yes	yes	no	no	no

A sketch map of Magra site

altitude 390 m a.s.l.



(The area is 6 sq. km approximately)

2. Slope profile survey

slope no.	bearing (deg)	length (m)	steepness (deg)	soil type	channel width (m)
1	10	291	4.3	f.r.comp	0
2	80	226	3.2	f.r.comp	0
3	90	259	6.9	f.r.comp	0
4	60	363	7.4	f.r.comp	2
5	160	320	15.1	f.r.comp	3.5
6	80	379	4.4	f.r.comp	0
7	140	373	3.9	f.r.comp	.7
8	160	264	3.5	f.r.comp	1
9	90	477	8.3	f.r.comp	1.5
10	90	431	4.9	f.r.comp	0

f.r.comp=ferric red compacted soil

3. Cross-profile survey

a.Vegetation cover, stones and land use type

pno	cpno	dsp	trs	shb	stn	oce	w/b	drgr	land use
1	lower	94	0	2	4	1	0	3	dry grass
1	middle	157	4	0	4	0	0	0	fruit trees
1	upper	230	4	0	4	0	0	0	fruit trees
2	lower	68	3	0	4	0	0	0	fruit trees
2	middle	117	3	0	3	0	0	0	fruit trees
2	upper	210	0	0	7	0	0	0	cleared
3	lower	59	0	7	3	0	0	0	n.vegetation
3	middle	128	4	0	0	0	0	0	fruit trees
3	upper	166	2	0	3	0	0	0	fruit trees
4	lower	76	3	2	7	1	0	0	n.vegetation
4	middle	247	1	0	8	0	0	0	fruit trees
4	upper	322	0	0	6	0	7	0	wheat/barley
5	lower	112	0	0	4	1	0	6	dry grass
5	middle	200	0	2	4	0	0	4	dry grass
5	upper	270	0	1	2	0	0	2	dry grass
6	lower	36	0	3	2	0	0	4	n.vegetation
6	middle	168	4	0	2	0	0	0	fruit trees
6	upper	312	4	0	3	0	0	0	fruit trees
7	lower	33	0	1	4	0	0	4	dry grass
7	middle	148	0	3	3	0	0	4	n.vegetation
7	upper	271	4	0	2	0	0	0	fruit trees
8	lower	50	0	3	3	0	0	0	n.vegetation
8	middle	98	1	0	2	0	0	1	fruit trees
8	upper	183	0	6	4	0	0	0	n.vegetation
9	lower	56	6	5	7	2	0	0	n.vegetation
9	middle	211	2	4	5	0	0	0	n.vegetation
9	upper	332	0	0	9	0	5	0	wheat/barley
10	lower	70	0	0	4	1	4	0	wheat/barley
10	middle	214	0	0	5	0	4	0	wheat/barley
10	upper	243	0	0	2	0	5	0	wheat/barley

b. Soil properties

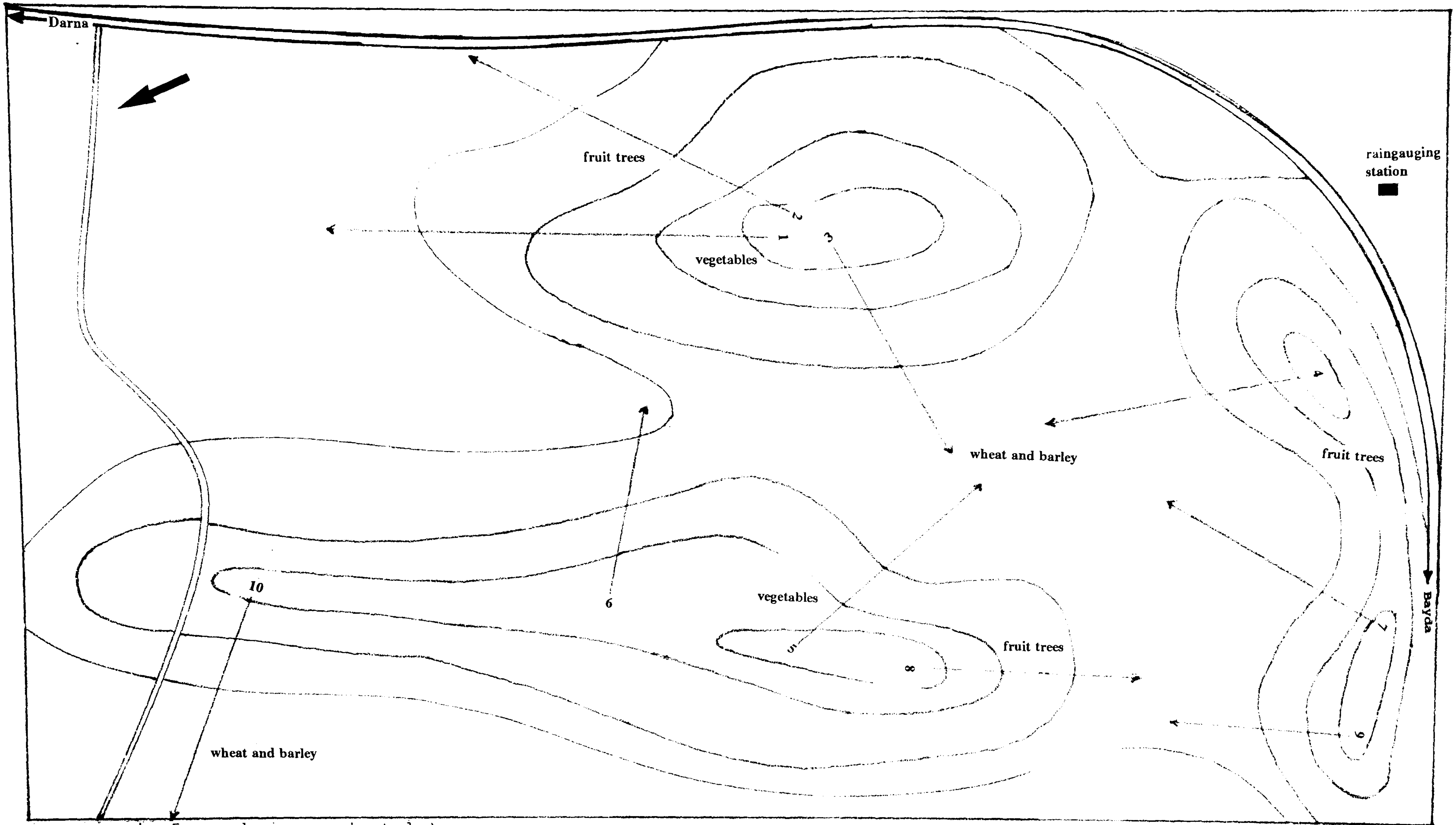
pno	cpno	soil texture	ir	om	oc	sd
1	lower	silt clay loam	2.8	2.5	1.25	28.6
1	middle	silt clay loam	7.6	3.2	1.59	25.2
1	upper	clay loam	1.2	3.6	1.8	15
2	lower	clay	2.1	3.8	1.88	26.8
2	middle	clay	3.2	2.4	1.2	21.4
2	upper	clay loam	4.0	1.5	1.5	16.4
3	lower	silt clay loam	.	1.9	.96	11.8
3	middle	clay	3.6	1.8	.92	19.2
3	upper	clay	3.0	2.2	1.08	15
4	lower	silt clay	.	2.2	1.11	17.6
4	middle	silt clay	1.6	2.3	1.13	15.4
4	upper	clay	3.0	2.6	1.28	18.6
5	lower	clay	.	0.9	.46	19.4
5	middle	clay	2.8	1.4	.69	22.2
5	upper	clay	3.0	1.7	1.7	19.6
6	lower	silt clay loam	3.6	1.3	.63	22.2
6	middle	clay	1.8	2.0	1.01	24.4
6	upper	clay	3.6	3.2	1.59	29.2
7	lower	silt clay loam	3.0	2.7	.71	22.6
7	middle	clay	2.4	2.4	.69	20.4
7	upper	clay	1.8	3.5	1.73	25.4
8	lower	clay loam	2.4	1.8	.92	26.4
8	middle	clay	2.1	1.3	.64	21.8
8	upper	clay	3.0	2.6	1.29	20.2
9	lower	silt clay loam	2.4	1.9	.68	19.6
9	middle	clay	2.4	1.5	.77	23
9	upper	clay	4.0	1.8	1.55	17.2
10	lower	clay loam	3.0	1.9	.95	27.4
10	middle	silt clay loam	3.2	1.5	.76	35.4
10	upper	silt clay loam	4.4	1.8	1.9	26

c. **Soil surface characteristics**

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	no	yes	yes	no	no	no
1	middle	no	no	no	no	no	no
1	upper	no	no	yes	no	no	no
2	lower	no	no	no	no	no	no
2	middle	no	no	no	no	no	no
2	upper	no	no	yes	no	no	no
3	lower	no	no	yes	no	no	no
3	middle	no	no	no	no	no	no
3	upper	no	yes	no	no	no	no
4	lower	no	no	yes	no	no	no
4	middle	no	no	yes	no	no	no
4	upper	no	yes	no	no	no	no
5	lower	no	yes	yes	no	yes	no
5	middle	no	yes	yes	no	yes	no
5	upper	no	yes	no	no	yes	no
6	lower	no	no	yes	no	no	no
6	middle	no	no	yes	no	no	no
6	upper	yes	no	yes	yes	no	no
7	lower	no	yes	yes	no	no	no
7	middle	yes	yes	no	no	no	no
7	upper	no	no	no	no	no	no
8	lower	no	no	no	no	no	no
8	middle	no	no	no	no	no	no
8	upper	yes	yes	no	no	no	no
9	lower	no	no	no	no	no	no
9	middle	yes	no	no	no	yes	no
9	upper	no	yes	yes	no	yes	no
10	lower	no	yes	yes	no	no	yes
10	middle	no	yes	no	yes	no	yes
10	upper	no	yes	no	yes	no	yes

A sketch map of Gobba site

altitude 580 m a.s.l.



(The area is 5 sq. km approximately)

2. Slope profile survey

slope no.	bearing deg.	length m	steepnes deg.	soil type	channel width(m)
1	30	371	2.2	vertic brown	0
2	70	273	2.8	vertic brown	0
3	290	417	3.6	vertic brown	0
4	20	331	4.6	vertic brown	0
5	160	662	4.8	vertic brown	0
6	120	864	3.2	vertic brown	0
7	70	408	5.0	vertic brown	0
8	200	539	3.7	vertic brown	0
9	40	545	4.4	vertic brown	0
10	300	594	3.5	ferric red	0

3. Slope profile survey

a. vegetation cover, stones and land use

pno	cpno	dsp	trs	shb	stn	oce	w/b	drgr	land use
1	middle	193	2	0	1	0	0	2	fruit trees
1	lower	77	0	0	4	1	8	0	whea/barley
1	upper	434	0	0	1	0	0	1	vegetable
2	upper	227	0	0	5	0	0	0	vegetable
2	lower	45	2	0	1	0	0	2	vegetable
2	middle	100	1	0	2	0	0	4	dry grass
3	middle	142	1	0	2	0	5	0	whea/barley
3	lower	67	1	0	3	0	6	0	whea/barley
3	upper	300	2	0	4	0	5	0	fruit trees
4	lower	49	2	0	4	0	3	0	dry grass
4	upper	243	0	0	6	0	5	0	whea/barley
4	middle	111	3	0	3	0	0	3	fruit trees
5	lower	110	0	0	4	0	6	0	whea/barley
5	middle	297	0	0	1	0	0	0	cleared
5	upper	537	0	0	3	0	0	0	vegetable
6	lower	60	0	0	5	0	6	0	whea/barley
6	middle	395	0	0	0	0	0	7	dry grass
6	upper	615	0	0	4	0	0	8	dry grass
7	lower	45	0	0	2	0	0	4	dry grass
7	middle	156	0	0	2	0	0	6	dry grass
7	upper	290	1	0	3	0	0	4	fruit trees
8	lower	95	2	0	1	0	0	0	fruit trees
8	middle	276	0	0	3	0	0	7	dry grass
8	upper	363	2	0	3	0	0	3	fruit trees
9	lower	60	0	0	2	0	4	0	whea/barley
9	middle	260	0	0	0	0	0	0	cleared
9	upper	351	0	0	1	0	3	1	whea/barley
10	lower	85	0	0	9	0	0	4	dry grass
10	middle	282	0	0	4	0	0	2	dry grass
10	upper	544	1	0	7	0	0	3	dry grass

b. Soil properties

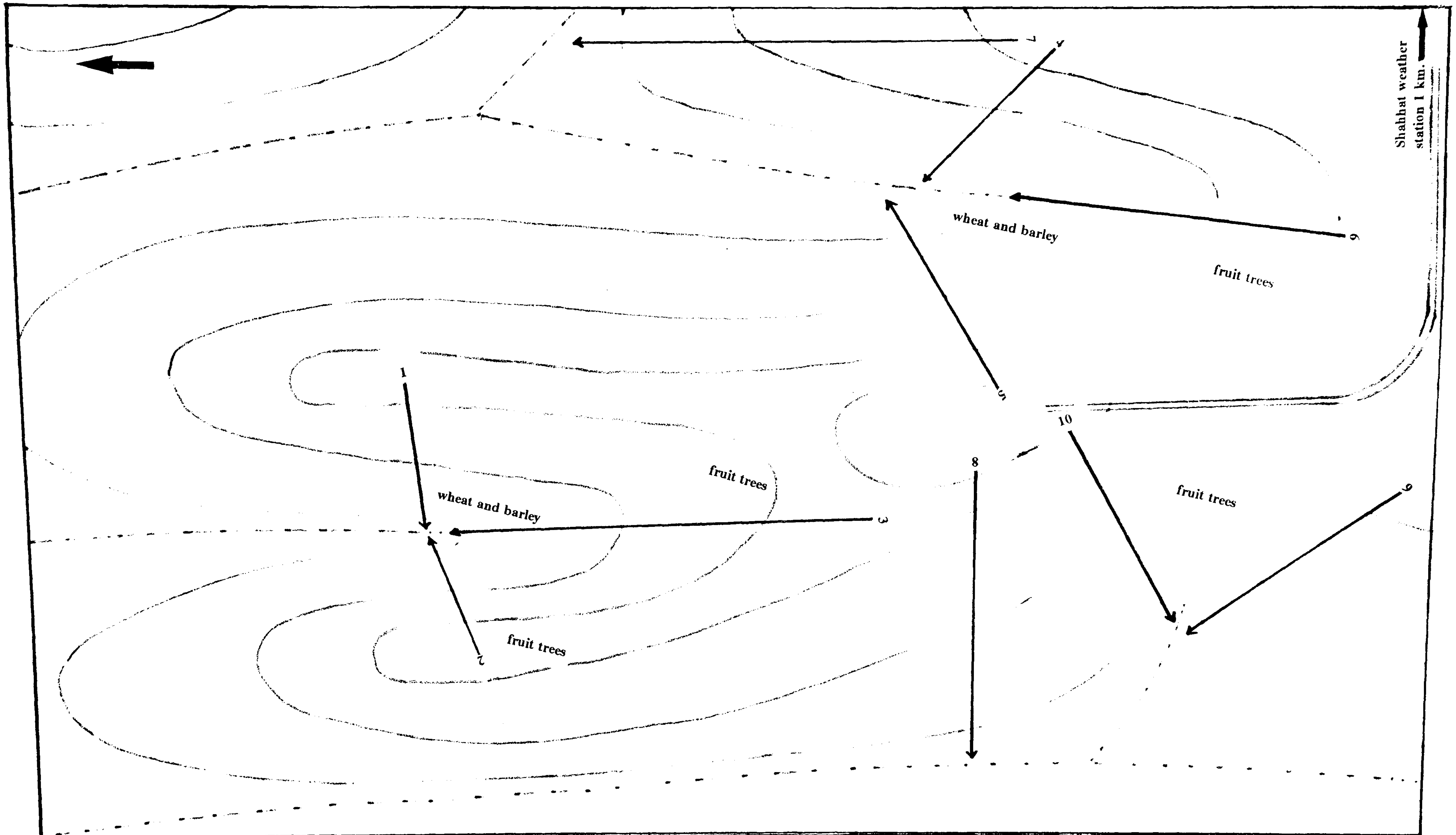
pno	cpno	soil texture	ir	om	oc	sd
1	lower	silt clay loam	2.4	1.8	.9	22.8
1	middle	silt clay loam	1.2	1.2	.6	48.6
1	upper	clay loam	6.3	1.3	.7	92
2	lower	clay	4.8	0.6	.3	70
2	middle	clay	2.8	0.9	.5	64.6
2	upper	clay loam	6.3	1.9	.9	31.2
3	lower	silt clay loam	5.2	1.4	.7	44.6
3	middle	clay	6.5	0.6	.3	71
3	upper	clay loam	7.2	2.0	1	20.8
4	lower	silt clay	2.2	1.8	.5	38.4
4	middle	silt clay	4.0	1.4	.7	41.8
4	upper	clay	2.0	1.6	.8	27.4
5	lower	clay	1.2	2.8	1.4	35.8
5	middle	clay	2.0	0.4	.2	61.2
5	upper	clay	1.8	0.9	.5	55
6	lower	silt clay loam	2.7	1.2	.6	53
6	middle	clay	3.0	0.4	.2	60.6
6	upper	clay	2.0	1.0	.5	60.6
7	lower	silt clay loam	1.2	0.3	.2	50.8
7	middle	clay	3.0	1.2	.6	59.2
7	upper	clay	2.0	2.2	1.1	25.4
8	lower	clay loam	4.8	1.3	.6	32.8
8	middle	clay	3.7	1.4	.7	81
8	upper	clay	1.8	1.6	.8	16.6
9	lower	clay	4.8	1.7	.8	43.4
9	middle	clay	4.0	0.9	.4	35.8
9	upper	silt clay loam	2.0	1.6	.8	55
10	lower	clay loam	4.0	1.6	1.8	20.4
10	middle	silt clay loam	2.0	2.0	1	34
10	upper	silt loam	.	2.0	1	24.2

c. **Soil surface characteristics**

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	no	no	no	yes	no	no
1	middle	no	yes	no	yes	no	no
1	upper	no	yes	no	no	no	no
2	lower	no	yes	no	yes	no	no
2	middle	no	yes	no	yes	no	no
2	upper	no	no	no	no	no	no
3	lower	no	yes	no	no	no	no
3	middle	no	yes	no	no	no	no
3	upper	no	no	no	no	no	no
4	lower	no	no	no	yes	no	no
4	middle	no	yes	no	no	no	no
4	upper	no	yes	no	no	no	no
5	lower	no	yes	no	no	no	no
5	middle	no	yes	no	no	no	no
5	upper	no	yes	no	no	no	no
6	lower	no	yes	no	no	no	no
6	middle	no	no	no	yes	no	no
6	upper	no	yes	no	yes	no	no
7	lower	no	yes	no	no	no	no
7	middle	no	yes	no	no	no	no
7	upper	no	no	no	no	no	no
8	upper	no	no	yes	no	yes	no
8	middle	no	yes	no	yes	no	no
8	lower	no	no	no	yes	no	no
9	lower	no	yes	no	no	no	no
9	middle	no	yes	no	no	no	no
9	upper	no	yes	no	no	no	no
10	lower	no	yes	no	no	no	no
10	middle	no	yes	no	no	no	no
10	upper	no	no	no	no	no	no

A sketch map of Shahhat site

altitude 625 m a.s.l.



(The area is 4 sq. km approximately)

2. Slope profile survey

slope no.	bearing deg.	length m	steepness deg.	soil type	channel width(m)
1	270	304	5.6	vertic brown	.75
2	90	439	8.8	vertic brown	0
3	350	479	5.8	vertic brown	0
4	320	439	7.1	ferric red	1.2
5	70	319	7.1	ferric red	0
6	360	303	5.9	ferric red	0
7	360	461	16.4	ferric red	3
8	270	384	9.1	ferric red	.5
9	310	409	7.5	ferric red	.7
10	220	279	6.5	ferric red	0

3. Cross-profile survey

a. Vegetation cover, stones and land use

pno	cpno	dsp	trs	shb	stn	oce	w/b	drgr	land use
1	lower	25	1	0	1	0	0	2	fruit trees
1	middle	74	1	0	2	0	0	0	fruit trees
1	upper	137	2	0	0	0	0	2	fruit trees
2	lower	35	1	0	3	0	0	3	dry grass
2	middle	165	2	0	2	0	0	0	fruit trees
2	upper	279	2	0	0	0	0	0	fruit trees
3	lower	40	0	0	3	0	3	0	whea/barley
3	middle	228	2	0	3	0	0	4	dry grass
3	upper	301	2	0	0	0	0	0	fruit trees
4	lower	66	1	0	4	0	0	3	dry grass
4	middle	257	2	0	2	0	0	4	fruit trees
4	upper	328	1	0	2	0	0	0	fruit trees
5	lower	49	0	0	5	0	3	0	dry grass
5	middle	105	0	0	2	0	0	2	dry grass
5	upper	211	2	0	1	2	0	0	fruit trees
6	lower	42	0	0	2	4	3	0	whea/barley
6	middle	127	4	0	6	0	0	4	fruit trees
6	upper	220	4	0	16	0	0	0	fruit trees
7	lower	79	1	0	3	0	0	2	dry grass
7	middle	213	0	0	4	0	3	4	whea/barley
7	upper	351	2	0	2	0	0	0	fruit trees
8	lower	127	0	0	4	0	5	0	whea/barley
8	middle	204	2	0	1	2	0	0	fruit trees
8	upper	289	1	0	4	0	0	3	fruit trees
9	lower	60	7	0	5	2	0	2	fruit trees
9	middle	154	3	0	3	0	0	5	fruit trees
9	upper	304	5	0	3	0	0	0	fruit trees
10	lower	60	0	0	3	0	0	7	dry grass
10	middle	96	4	0	3	0	0	2	fruit trees
10	upper	150	3	0	3	0	0	4	fruit trees

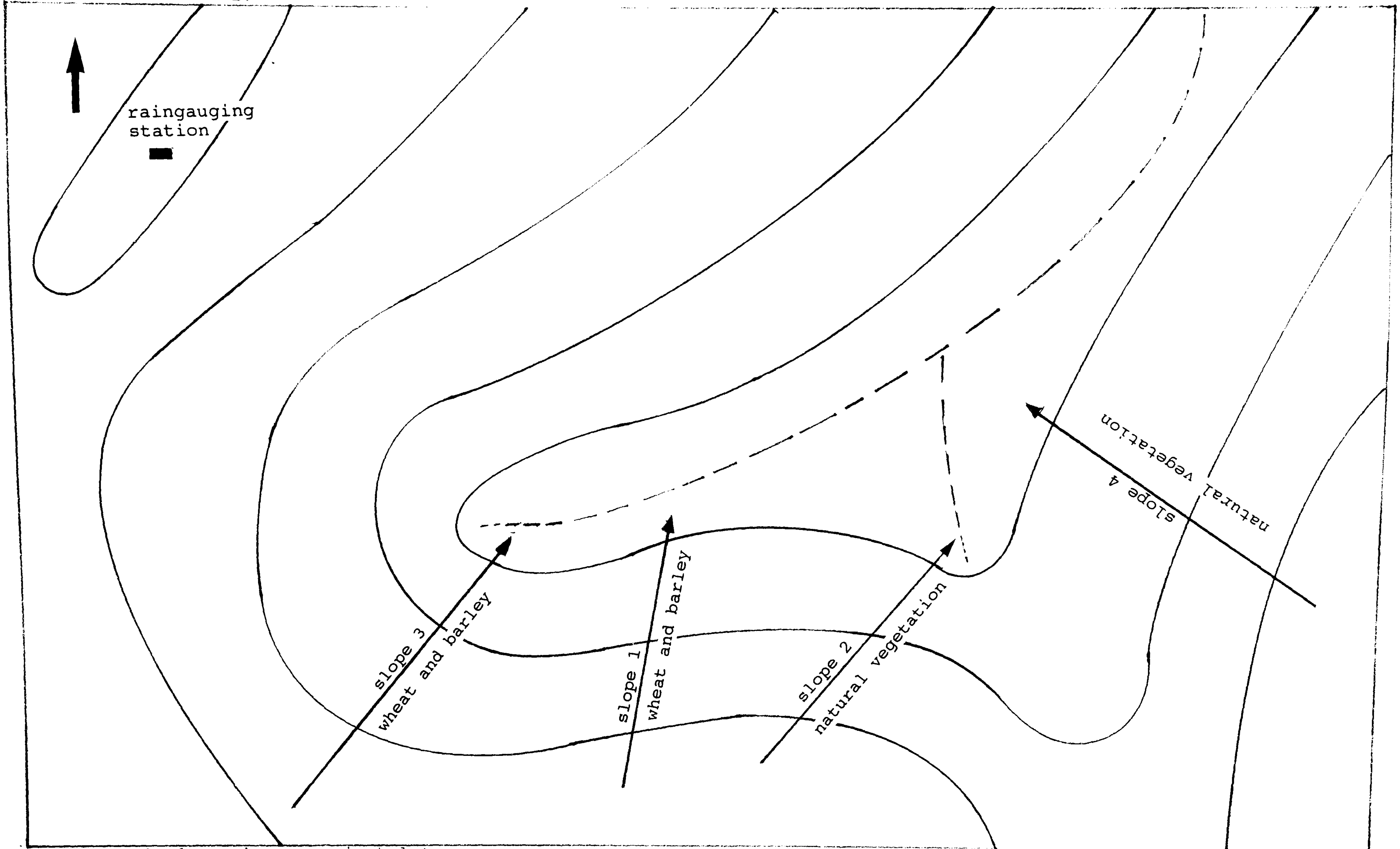
b. Soil properties

pno	cpno	soil texture	ir	om	oc	sd
1	lower	silt loam	3.6	3.0	1.5	23.2
1	middle	loam	8.4	2.1	1.1	17
1	upper	silt clay loam	9.0	1.7	.8	19.2
2	lower	loam	3.6	2.3	1.1	21.2
2	middle	clay loam	7.0	2.1	1.1	16.4
2	upper	clay	8.4	1.5	.8	22.2
3	lower	loam	4.2	2.3	1.7	26.2
3	middle	clay loam	6.3	2.1	1.0	21
3	upper	silt clay loam	6.6	3.4	1.2	22.2
4	lower	silt clay loam	8.4	1.8	.9	20.6
4	middle	clay	7.4	2.1	1.1	18
4	upper	silt clay	7.8	2.1	1.0	19.4
5	lower	clay loam	8.4	3.9	1.9	25.8
5	middle	clay loam	7.6	2.7	1.4	21.6
5	upper	clau loam	9.0	2.0	1.0	24
6	lower	loam	8.7	3.1	1.5	27.6
6	middle	clay loam	8.0	2.7	1.4	16.4
6	upper	clay loam	9.0	2.9	1.5	14.6
7	lower	clay	.	1.2	2.1	23.4
7	middle	clay loam	8.0	2.9	1.5	18.2
7	upper	sandy clay	7.2	2.1	1.0	20.2
8	lower	clay loam	.	3.1	1.5	16.8
8	middle	clay loam	7.8	3.2	1.6	28.6
8	upper	clay	2.7	2.7	1.3	30.4
9	lower	clay loam	8.4	5.1	2.5	37.8
9	middle	silt clay loam	6.0	3.3	1.6	41.6
9	upper	clay loam	6.8	3.2	1.6	24.4
10	lower	clay loam	3.4	2.4	1.2	37.8
10	middle	clay laom	2.4	2.5	1.3	24.6
10	upper	clay	2.4	2.5	1.3	20.2

c. **Soil surface characteristics**

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	no	yes	yes	no	no	no
1	middle	no	no	no	yes	no	no
1	upper	no	yes	no	no	no	no
2	lower	no	no	no	no	no	no
2	middle	no	yes	no	no	no	no
2	upper	no	no	no	yes	no	no
3	lower	no	yes	yes	no	no	no
3	middle	no	yes	no	no	no	no
3	upper	no	no	no	no	no	no
4	lower	no	no	no	yes	no	no
4	middle	no	no	no	no	no	no
4	upper	no	no	no	no	no	no
5	lower	no	no	no	no	no	no
5	middle	no	no	yes	no	no	no
5	upper	no	no	no	no	no	no
6	lower	no	no	no	no	no	no
6	middle	no	no	no	no	no	no
6	upper	no	no	no	no	no	no
7	lower	no	no	no	no	no	no
7	middle	no	no	no	no	no	no
7	upper	no	no	no	yes	no	no
8	lower	no	no	no	no	no	no
8	middle	no	yes	no	no	no	no
8	upper	no	no	no	no	no	no
9	lower	no	yes	no	no	no	yes
9	middle	no	yes	no	no	no	no
9	upper	no	no	no	no	no	no
10	lower	no	no	no	no	no	yes
10	middle	no	no	no	no	no	no
10	upper	no	no	no	no	no	no

A sketch map of Al-Kouf site
altitude 608 m a.s.l.



(The area is 1 sq. km approximately)

2. Slope profile survey

slope no.	bearing (deg)	length (m)	steepness (deg)	soil type	channel width(m)
1	30	74	3.1	ferric red	0
2	60	54	2.0	ferric red	0
3	50	61	4.5	ferric red	0
4	320	54	5.0	ferric red	0

2. Cross profile survey

a. Vegetation cover, stones and type of land use

pno	cpno	dsp	trs	shb	stn	oce	w/b	drgr	land use
1	lower	10	0	0	4	0	8	0	wheat/barley
1	middle	28	0	0	6	0	6	0	wheat/barley
1	upper	62	0	0	7	0	4	0	wheat/barley
2	lower	5	1	2	4	0	0	11	n.vegetation
2	middle	24	0	3	6	0	0	8	n.vegetation
2	upper	32	0	4	5	1	0	6	n.vegetation
3	lower	4	0	0	4	0	7	2	wheat/barley
3	middle	16	0	0	5	0	4	3	wheat/barley
3	upper	49	0	2	5	0	4	2	wheat/barley
4	lower	5	0	9	2	0	0	5	n.vegetation
4	middle	13	0	9	2	0	0	4	n.vegetation
4	upper	38	1	6	1	0	0	5	n.vegetation

b. Soil properties

pno	cpno	soil texture	ir	om	oc	sd
1	lower	clay	9.0	3.2	1.59	80
1	middle	silt loam	8.0	3.6	1.79	60
1	upper	loam	8.0	3.5	1.74	50
2	lower	clay loam	15.0	3.5	1.73	55
2	middle	clay	14.0	3.4	1.71	40
2	upper	clay	14.0	3.5	1.76	40
3	lower	clay	12.0	2.4	1.19	70
3	middle	clay	12.0	3.2	1.62	60
3	upper	clay	10.0	2.5	1.25	55
4	lower	clay	6.0	3.4	1.68	50
4	middle	clay	6.0	2.0	1.01	40
4	upper	clay	5.0	2.9	1.46	35

c. Soil surface characteristics

pno	cpno	surfcrus	cracks	compact	farmprac	biolact	ert
1	lower	no	no	no	no	no	no
1	middle	no	yes	no	no	no	no
1	upper	no	yes	no	no	no	no
2	lower	no	yes	no	no	no	no
2	middle	no	yes	no	no	no	no
2	upper	no	yes	no	no	no	no
3	lower	no	yes	no	no	no	no
3	middle	no	yes	no	no	no	no
3	upper	no	yes	no	no	no	no
4	lower	no	yes	no	no	no	no
4	upper	no	yes	no	no	no	no
4	middle	no	yes	no	no	no	no

Appendix 2a

Annual rainfall

Shahhat precipitation 1945-1993 in mm

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
.	.	93.5	1.5	5.8	0.0	0.0	7.1	5.3	16.0	98.8	133.5
53.6	110.4	61.1	0.5	1.5	0.0	0.0	0.0	27.2	35.8	68.1	172.6
288.4	31.4	6.1	2.3	0.0	0.0	7.9	0.0	0.5	18.8	198.0	70.5
80.4	147.3	71.0	25.4	3.8	0.3	0.0	0.0	1.3	4.1	143.3	146.6
178.7	72.6	80.0	2.3	26.9	3.6	0.0	7.4	0.0	14.2	41.4	136.3
140.9	46.6	75.9	40.9	72.1	5.6	0.0	1.8	5.1	14.4	90.7	56.5
122.0	64.0	31.4	1.5	1.1	0.0	2.4	0.0	9.7	75.6	68.7	83.3
140.4	122.0	67.7	0.1	3.4	0.0	0.0	0.0	11.3	32.6	84.4	203.0
131.0	64.4	96.8	3.7	9.8	1.4	0.0	0.0	11.1	25.9	115.4	75.3
153.0	85.9	85.0	19.0	0.0	0.0	1.0	42.0	4.0	371.0	95.0	107.9
26.0	15.9	87.0	16.0	1.0	0.0	0.0	4.0	3.0	24.0	83.0	84.9
63.9	129.9	68.0	2.0	12.0	0.0	0.0	0.0	7.0	16.0	20.0	134.0
219.0	52.9	132.0	19.0	30.0	5.0	0.0	0.0	10.0	39.0	49.0	143.0
123.1	020.3	013.8	13.7	0	0	0	0	2.5	5.8	039.6	064.9
166.9	117.3	024.4	28.6	3.4	0	7.6	0.1	0	076.5	031.8	095.3
132.4	030.6	106.5	15.0	9.7	0	0	0	9.0	0	094.0	094.6
096.3	284.5	034.5	6.4	4.8	0	0	0	7.2	097.1	9.8	261.0
188.9	152.3	020.3	2.9	5.0	0.5	0.9	0	17.5	093.9	014.9	269.4
114.0	069.3	054.6	16.5	24.0	3.0	3.3	0	0	115.2	060.0	8.0
097.6	081.0	040.7	4.6	14.7	14.9	0	0	15.0	3.6	103.3	115.6
126.4	101.5	072.5	62.8	5.0	0	0	3.1	0	023.9	049.7	140.5
217.9	035.0	109.9	22.5	0	4.5	0	0	62.2	046.0	033.5	168.5
125.5	085.1	108.9	33.1	5.9	0	0	4.8	7.5	145.2	054.8	115.4
199.2	090.6	055.9	0.3	3.3	31.4	2.3	0	7.1	105.6	096.4	125.0
243.2	033.0	072.8	34.5	21.3	0	0	0	0	150.1	026.6	115.7
064.6	061.4	145.6	25.0	9.0	0	0	0	28.5	034.9	096.5	016.7
098.9	131.8	023.9	32.8	1.7	0	0.7	0	22.8	041.1	110.4	032.5
020.8	044.4	060.5	65.7	3.7	0	0	0	0	168.4	017.7	074.8
074.9	097.8	076.6	32.8	1.7	0	0	0	0.9	076.3	048.6	031.8
147.8	066.8	036.9	5.9	1.3	0	0	7.0	0.3	013.2	072.3	127.5
152.4	055.6	7.2	37.2	1.0	1.2	0	0.4	2.2	037.6	024.5	106.3
168.0	110.9	093.4	41.3	15.3	4.9	0.3	0.3	17.5	040.8	066.0	048.4
083.7	019.3	017.3	81.0	1.6	0	0	0	66.4	016.3	017.4	357.2
146.1	165.0	087.0	15.0	0.1	010.5		0	31.4	106.6	022.1	122.5
060.3	121.8	022.3	22.4	3.3	1.2	0	0	1.0	089.4	076.9	143.5
061.8	145.2	085.9	26.7	0.4	0	0	0	2.2	029.4	3.0	037.2
332.1	152.2	015.2	2.2	15.6	0.8	0.3	0	0	7.7	146.3	052.9
041.2	109.6	044.3	17.0	0	0	0	0	0	2.0	062.0	133.9
168.0	068.2	104.3	25.5	6.9	0	0	13.5	17.0	046.8	139.4	062.9
092.8	036.9	055.6	43.1	0	0	0	0	0.4	029.5	163.5	041.4
148.1	0	0	21.0	13.5	0	0	0.5	0.1	091.7	038.0	087.2
109.8	033.6	062.5	0	31.8	0	0	0	36.0	020.0	060.1	127.4
081.9	057.8	163.4	61.9	0	0	0	0	0	2.6	074.0	117.6
093.5	118.4	074.1	2.4	2.3	0	0	0	3.9	104.3	043.5	263.7
119.0	063.6	230.1	0	2.7	4.3	0	0	0	040.2	071.4	035.1
168.9	074.5	011.7	4.6	0.4	0	0	14.5	11.5	3.5	055.0	065.7
093.7	107.0	016.2	24.2	24.6	0	0.6	0	2.9	17.3	113.5	434.8
041.6	154.1	031.0	6.8	16.4	0	0.4	0	1.5	0	97.2	105.1
189.3	47.1	65.9	0.4	9.6	0	0	0	15.3	48.9	26.3	40.1

Bayda precipitation 1958-1990 in mm

Jan	Feb	Mar	Apr	May	J	Jul	Aug	Sep	Oct	Nov	Dec
.	.	.	0	0	0	0	0	1.5	010.0	049.5	050.5
243.0	152.5	032.0	8.5	1.5	0	7.0	0	0	132.2	026.0	149.0
109.5	015.5	087.5	021.5	11.0	0	0	0	0	0	086.5	104.0
125.5	300.0	021.5	4.5	4.0	0	0	0	0	078.5	025.0	235.2
126.0	134.5	016.5	5.5	3.5	0	0	0	12.5	9.0	8.0	125.5
090.0	084.5	056.0	030.0	13.0	0	0	0	0	056.0	039.3	002.5
057.3	085.0	048.0	0	0	0	0	0	0	040.0	011.0	068.5
111.3	088.2	044.2	3.4	2.1	0	0	0	0	040.0	042.0	147.0
242.0	035.0	7.5	0	0	0	0	0	40.0	0	043.5	074.5
111.2	074.0	0	0	0	0	0	0	0	031.0	062.5	133.5
196.0	019.0	0	0	0	0	0	0	7.0	075.0	076.1	090.0
214.0	028.7	044.1	025.5	9.2	0	0	0	0	106.6	021.0	083.3
091.0	053.4	088.8	016.0	3.9	0	0	0	14.0	024.8	076.2	012.2
087.0	114.7	014.6	024.3	0.7	0	0	0	11.2	029.2	087.2	023.4
018.3	038.6	057.6	147.1	0	0	0.5	3.	2.0	109.5	021.0	044.1
080.0	090.0	075.1	0	0	0	0	0	2.0	089.3	042.4	027.2
159.3	083.2	038.1	2.0	0	0	0	0	0	0	027.0	152.6
149.2	034.7	0	030.7	0	0	0	0	0	039.0	024.9	009.8
147.8	096.5	057.0	027.0	6.6	0	0	0	8.6	039.0	060.6	026.5
057.5	015.3	020.5	082.0	0.7	0	0	0	32.5	011.6	018.0	046.3
087.7	118.1	053.1	011.3	0	0	0	0	15.4	075.7	017.5	075.5
053.1	077.9	032.4	016.6	1.4	0	0	0	0.5	8.0	056.5	138.7
059.0	085.5	088.6	063.6	11.5	0	0	0	0	4.0	022.0	024.4
252.5	159.8	2.5	4.6	10.2	0	0	0	0	014.2	147.8	049.3
042.5	116.0	030.0	017.6	0	0	0	0	0	7.0	058.0	114.8
185.9	059.5	088.4	0	0	0	0	16.	22.0	035.5	095.1	082.0
059.7	022.0	035.5	046.5	0	0	0	0	0	018.0	176.5	055.0
132.2	091.0	6.6	0	0	0	0	0	0	068.4	053.0	099.0
113.0	035.1	032.0	0	0	0	0	0	77.0	038.0	028.0	126.5
126.5	076.0	055.2	144.0	87.0	0	0	0	0	0	086.0	096.0
098.0	111.5	073.0	0	0	0	0	0	0	029.3	004.0	185.8
103.0	056.9	305.0	0	0	0	0	0	0	052.3	054.0	068.0
135.5	044.5	0	0	0	0	0	0	0	0	043.0	025.0

Batta precipitation in mm 1965-90

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
.	.	.	.	.	0	0	0	0	0	23.0	087.5
181.0	016.5	0	0	0	0	0	0	0	0	48.4	285.4
138.2	090.0	116.0	0.5	0	0	0	10.3	0	28.1	31.6	022.0
219.4	029.0	058.6	0	6.5	0	0	0	0	138.0	.	087.5
329.4	014.5	061.6	024.0	048.5	0	0	0	24.5	0	.	081.1
051.8	048.8	052.4	016.0	0	0	0	0	17.5	7.7	51.0	7.5
160.0	140.0	046.3	069.5	0	0	0	0	42.0	0	79.0	024.5
038.0	030.5	027.5	213.0	010.0	0	0	0	0	68.7	8.0	030.0
091.0	099.0	043.0	022.0	0	0	0	0	12.0	64.0	67.5	021.0
131.5	079.0	034.0	6.0	0	0	0	0	0	11.0	52.5	147.7
142.0	046.0	0	0	7.0	0	0	0	0	17.0	62.0	.
151.5	128.0	078.0	7.5	0	0	0	0	0	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
164.0	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	053.0	.	.	.	.	.	.	.	.	.	064.0
296.0	100.0	010.0	0	0	0	0	0	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	0	0	0	0	0	.	.	83.0	192.0
177.0	026.0	7.0	0	0	0	0	0	.	.	45.0	157.0
126.0	026.0	080.0	036.0	0	0	0	0	0	0	60.0	088.3
068.1	094.6	067.3	0	0	0	0	0	0	.	.	037.0
.	.	.	0	0	0	0	0	0	30.0	20.0	047.0
099.0	0	0	0	0	0	0	0	0	0	26.0	033.0

Al-Kouf precipitation 1980 - 1993

Jan	Feb	Mar	Apr	May	J	Jul	A	Sep	Oct	Nov	Dec
.	.	.	.	.	.	.	.	06.7	027.5	004.6	039.0
313.2	159.3	013.0	04.8	13.9	0.6	0.8	0	0	023.6	157.7	026.7
035.2	105.5	043.0	21.6	02.7	0	0	0	06.5	007.4	034.4	094.3
014.4	041.6	082.7	12.0	05.6	3.7	0	0	0	033.5	135.0	066.8
082.3	056.4	028.7	0	0	0	0	0	15.3	115.4	044.5	141.6
061.9	020.4	031.4	12.3	0	0	0	0	0.3	067.4	036.9	072.1
082.4	016.2	030.9	0	41.4	0	0	0	72.4	057.1	056.2	141.7
043.1	045.1	144.6	37.6	0	0	0	0	0	0	109.9	089.2
076.1	129.7	062.4	0	0	0	0	0	0	043.0	001.1	129.9
060.3	040.9	212.5	0	0	0	0	0	0	019.0	092.2	052.6
113.1	037.2	28.7	8.7	13.7	0	0	0	0	011.6	079.4	020.3
100.7	059.4	028.7	08.7	13.7	0	0	0	0	0	063.0	168.3
65.3	87	7.9	8.5	0	0	0	0	0	0	57.2	30.6
93.1	47.3	18.1	7.8	0	0	0	0	0.4	16	32.6	37.4

Gobba precipitation 1958-1990 in mm

Jan	Feb	Mar	Apr	May	J	Jul	A	Sep	Oct	Nov	Dec
116.9	1.7	5.0	3.0	0	0	0	0	0	13.5	013.7	023.0
117.9	171.0	.	10.5	0	0	0	0	0	183.0	4.0	113.0
324.0	034.2	34.0	10.0	0	0	0	0	0	0	074.7	036.4
034.5	293.3	17.3	3.3	0	0	0	0	3.0	70.0	018.0	099.0
125.5	073.0	3.5	0	0	0	0	0	0	4.5	049.0	137.0
140.0	170.0	45.5	18.5	4.0	0	0	0	3.5	34.5	032.5	3.5
044.9	073.7	23.5	0	8.5	0	0	0	0	0	057.9	074.5
056.7	063.0	33.5	25.0	0	0	0	0	0	54.2	9.3	047.3
181.5	014.5	56.0	0	0	0	0	0	16.5	0	0	076.5
079.5	0	57.0	10.7	0	0	0	0	0	143.0	050.0	017.0
104.0	031.0	26.0	0	0	0	0	0	0	114.0	027.0	097.5
213.0	019.0	33.0	0	0	0	0	0	0	60.0	020.0	023.7
071.0	020.5	19.7	6.0	4.0	0	0	0	13.5	147.5	122.5	030.0
058.0	040.5	19.3	19.5	0	0	0	0	76.5	31.0	118.5	030.0
011.0	040.2	39.5	96.0	3.0	0	0	0	1.5	89.0	020.0	039.0
061.0	027.3	57.8	9.5	6.5	0	0	0	1.0	44.0	031.0	013.5
114.0	063.0	25.5	2.5	0	0	0	0	9.5	1.0	6.5	078.0
119.0	075.0	0	21.0	8.0	0	0	0	0	44.5	7.8	081.5
126.5	081.2	94.5	4.0	14.0	7.5	0	0	0	57.5	049.6	027.0
053.0	011.5	31.5	29.5	0	0	0	0	39.5	7.5	8.5	244.5
172.0	070.5	81.0	25.5	0	0	0	0	16.0	126.0	023.0	070.9
049.5	062.0	10.5	14.0	0	26.0	0	0	0	56.0	111.0	9.3
4.8	142.7	75.5	38.0	0	0	0	0	0	13.0	0	030.9
192.9	080.0	0	0	0	0	0	0	0	0	074.5	095.0
035.8	138.5	35.5	6.9	3.5	0	0	0	0	0	034.8	076.7
084.0	058.5	45.0	0	0	0	0	0	0	35.5	113.5	020.0
031.0	067.5	37.0	0	0	0	0	0	0	76.0	111.0	027.0
114.0	082.0	0	0	0	0	0	0	0	44.5	7.0	114.5
045.5	021.0	54.5	0	0	0	0	0	75.5	43.0	129.0	081.6
072.6	023.0	109.0	3.0	0	0	0	0	0	0	028.3	089.5
067.0	097.5	29.0	0	0	0	0	0	1.5	49.6	038.5	165.0
132.0	036.0	127.6	0	0	0	0	0	0	38.5	036.5	058.2
102.6	044.0	0.8	0	0	0	0	0	0	0	3.5	0

Faydia precipitation in mm 1967-82

Jan	Feb	Mar	Apr	May	Jun	Jul	A	Sep	Oct	Nov	Dec
036.8	039.0	0	0	0	0	0	0	65.3	157.0	012.0	042.0
111.0	083.2	103.0	0	0	0	0	0	0	107.0	063.9	176.0
129.0	075.0	100.0	0	35.0	0	0	0	0	019.0	029.0	082.0
016.0	050.0	031.0	031.0	0	0	0	0	08.0	0	0	034.0
112.0	129.8	003.9	018.2	01.9	0	0	0	22.0	057.0	035.0	042.0
012.0	022.0	021.0	102.0	0	0	0	0	0	086.0	014.0	036.0
062.0	073.0	053.4	023.0	00.1	0	0	0	0	039.7	023.0	017.0
142.5	055.0	035.7	0	0	0	0	0	0	004.0	050.5	107.5
107.5	036.5	009.5	033.0	05.0	0	0	0	0	049.0	009.0	047.5
098.0	079.0	058.0	003.0	0	10.0	0	0	03.0	049.0	020.0	019.0
054.0	005.0	022.0	046.0	0	0	0	0	13.0	003.0	036.0	256.0
106.0	104.0	089.2	010.0	0	0	0	0	17.0	085.5	006.0	079.5
069.0	065.6	013.0	010.0	0	0	0	0	0	019.0	062.5	129.5
042.5	124.0	071.0	005.0	0	0	0	0	0	0	0	030.2
198.0	108.2	0	0	10.0	0	0	0	0	007.0	083.4	036.0
021.0	112.5	041.5	016.0	0	0	0	0	0	0	028.0	086.0

Al-Marj precipitation 1958-1991 in mm

Jan	Feb	Mar	Apr	May	Jun	Jul	A	Sep	Oct	Nov	Dec
099.0	005.0	012.3	0	0	0	0	0	0	011.5	033.0	020.5
124.0	035.5	020.9	001.5	0	0	0	0	0	014.7	027.8	064.0
059.5	009.5	016.0	002.5	0	0	0	0	0	0	037.0	127.2
097.0	245.5	012.0	0	0	0	0	0	0	039.5	0	152.5
128.5	108.1	020.4	000.9	12.0	0	0	0	03.2	033.0	005.0	.
104.0	.	002.7	009.8	26.5	4.6	0	0	.	067.1	007.6	0
037.5	032.8	033.0	0	0	0	0	0	.	.	070.0	045.5
133.0	074.5	037.1	030.7	0	0	.	.	.	010.3	012.8	124.0
135.5	018.5	069.0	016.5	0	0	0	0	0	0	015.5	187.5
079.0	037.0	092.5	0	0	0	0	0	0	028.5	008.0	051.5
143.0	031.0	018.0	0	0	0	0	0	0	054.0	032.0	098.5
188.0	007.0	050.5	025.5	12.0	0	0	0	0	027.0	003.0	057.0
038.0	039.0	049.0	016.0	08.0	0	0	0	0	0	030.0	010.0
094.0	104.0	015.5	022.5	0	0	0	0	20.0	013.0	036.0	026.0
046.0	034.0	027.0	159.5	05.5	0	0	04.5	0	108.0	0	053.0
069.5	099.2	046.0	015.0	0	0	0	0	0	070.5	030.0	019.5
130.5	062.5	022.4	0	02.0	0	0	0	0	0	.	143.5
091.0	039.0	0	014.0	0	9.5	0	0	0	021.0	.	045.0
149.0	.	077.5	.	13.5	0	0	0	0	040.5	039.0	021.5
020.7	018.3	006.5	073.5	0	0	0	0	.	.	.	.
.	024.5	.	.	.	.	.	.	.	047.1	095.7	081.7
.	.	.	.	.	.	.	.	.	.	.	.
064.7	077.0	045.8	013.1	0	0	0	0	0	021.9	002.1	049.7
337.7	135.0	012.0	0	0	0	0	0	0	017.5	138.3	049.0
052.6	111.1	074.5	007.0	0	0	0	0	0	004.3	030.8	075.5
110.4	029.3	067.6	006.0	0	0	0	0	02.3	059.8	070.2	105.9
058.4	032.0	007.2	0	0	0	0	0	0	007.2	070.5	050.5
147.3	038.0	026.2	014.7	06.5	0	0	0	0	094.2	044.5	035.5
073.9	043.6	052.5	000.3	43.5	1.0	0	0	39.0	054.5	040.8	177.2
050.0	062.2	106.7	044.6	0	0	0	0	09.0	0	071.0	059.5
057.5	089.3	073.9	0	0	0	0	0	0	015.5	023.5	249.3
063.1	020.5	173.4	0	0	0	0	0	0	021.8	041.9	053.6
089.8	028.1	004.2	0	0	0	0	0	0	0	034.0	035.8
044.5	010.8	013.9	012.0	0	.	.	.	.	.	.	.

Gaygab precipitation in mm 1967-83

Jan	Feb	Mar	Apr	May	Jun	Jul	A	Sep	Oct	Nov	Dec
037.0	040.0	0	0	0	0	0	0	0	028.3	004.8	032.5
112.1	090.7	119.5	0	0	0	0	0	27.5	016.6	0	036.0
183.0	015.0	060.5	0	0	0	0	0	0	022.0	016.0	054.0
034.5	039.0	054.0	54.1	0	0	0	0	02.5	046.5	001.0	006.0
084.5	142.0	004.5	20.5	02.0	0	0	0	09.0	062.0	047.0	037.0
024.5	038.5	047.0	90.0	0	0	0	0	0	073.0	033.0	029.0
039.0	030.0	035.0	13.0	0	0	0	0	0	019.0	027.0	021.0
069.5	053.0	030.5	02.0	0	0	0	0	0	001.0	024.0	114.5
079.5	038.0	003.0	25.0	0	0	0	0	06.0	005.0	030.5	049.0
110.0	053.5	071.0	04.0	10.5	0	0	0	02.0	013.0	029.0	015.8
034.6	013.0	028.0	69.0	0	0	0	0	0	0	015.0	241.0
146.0	119.0	088.0	0	0	0	0	0	0	073.0	006.0	071.0
034.0	064.0	019.5	17.0	10.0	5.0	0	0	00.5	023.5	062.5	123.0
042.0	129.5	092.0	23.0	0	0	0	0	0	0	001.0	018.8
266.5	143.6	010.5	06.0	10.0	0	0	0	0	030.5	125.5	029.0
043.0	172.5	052.4	10.5	04.5	0	0	0	10.0	003.0	026.0	117.5
135.5	063.5	066.5	13.0	04.0	0	0	0	.	.	.	.

Labrag precipitation in mm 1967-83

Jan	Feb	Mar	Apr	May	Jun	Jul	A	Sep	Oct	Nov	Dec
072.0	122.9	050.5	14.5	0	0	0	0	0	007.6	020.0	086.0
054.5	0	101.0	0	0	0	0	0	0	111.0	087.0	0
291.0	028.0	025.0	48.0	0	0	0	0	0	022.0	0	0
020.6	0	022.0	47.0	21.0	17.0	0	0	06.0	022.5	185.5	007.5
074.5	101.0	015.0	40.0	02.5	0	0	0	0	021.0	045.5	054.0
026.5	030.0	045.5	125.0	05.0	0	0	0	02.5	104.0	038.0	040.5
036.5	045.0	027.0	20.0	08.0	0	0	0	0	062.0	045.0	023.0
070.9	028.3	026.0	0	0	0	0	0	02.0	0	022.0	067.5
058.0	062.0	0	45.0	0	0	0	0	05.8	014.3	089.0	093.0
093.0	043.0	052.0	12.0	11.0	0	0	0	0	031.5	031.2	016.5
039.0	016.0	019.0	0	0	0	0	0	13.0	013.0	008.0	313.0
101.0	080.0	028.0	11.0	0	0	0	0	0	053.0	002.7	040.0
033.0	039.0	005.5	17.0	21.1	0	0	0	00.6	028.4	097.5	112.7
043.2	090.5	056.0	30.1	0	0	0	0	0	0	0	026.0
241.0	123.0	008.0	0	09.0	0	0	0	0	011.8	103.6	026.2
015.4	133.5	036.0	0	0	0	0	0	0	0	025.0	121.0
144.5	59.5	87.5	0	0	0	0	0	.	.	.	.

Susa precipitation 1958-1990 in mm

Jan	Feb	Mar	Apr	May	Jun	Jul	A	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	3.5	012.6	023.0	038.8
129.4	098.5	8.4	2.3	4.7	0	0	0	0	118.2	011.2	078.2
072.5	013.5	055.6	4.1	5.0	0	0	0	0	0	037.5	086.7
062.5	180.5	016.5	1.5	0	0	0	0	0.5	093.5	0	161.5
142.5	139.5	.	.	0	0	0	0	29.0	097.5	1.0	099.5
108.0	056.0	031.5	26.5	0	0	0	0	0	031.0	064.0	6.0
081.0	090.0	022.0	0	6.0	12.0	0	0	0	1.5	048.0	101.5
154.2	111.0	053.9	45.9	0	0	0	0	0	056.0	015.0	053.0
202.0	023.0	087.0	5.0	0	0	0	0	154.0	1.0	010.0	088.5
055.5	084.0	059.0	16.0	0	0	0	0	0	092.0	033.5	0
098.5	024.4	043.0	0	0	0	0	0	3.0	125.5	081.5	070.0
121.5	015.0	029.0	29.0	23.0	0	0	0	0	056.0	026.5	041.5
057.5	026.5	057.0	11.0	6.0	0	0	0	0	6.0	020.0	020.0
051.0	105.5	010.5	4.3	0	0	0	0	23.0	0	.	018.5
033.5	050.5	030.5	59.5	0	0	0	0	5.5	075.5	011.5	028.5
065.0	087.5	038.8	22.5	3.0	0	0	0	0	082.5	026.5	011.8
106.9	061.0	016.4	0	0	0	0	0	3.0	8.3	025.2	064.0
086.0	039.0	0	29.0	0	0	0	0	0	056.5	027.0	095.5
071.0	059.0	029.0	0	0	0	0	0	.	025.0	023.5	031.0
033.0	8.5	4.5	36.0	0	0	0	0	35.0	1.0	8.5	016.5
121.8	081.5	097.4	0	0	0	0	0	4.5	098.0	9.5	073.0
031.0	079.3	3.5	6.0	0	4.5	0	0	1.5	033.0	054.0	087.5
024.5	071.0	019.5	18.0	8.0	0	0	0	0	103.5	.	065.0
264.5	083.0	012.0	0	0	0	0	0	0	3.0	118.5	052.5
012.0	076.5	027.5	12.0	2.0	0	0	0	0	030.0	.	.
.	.	.	.	.	.	.	.	27.0	172.0	058.0	039.0
030.5	014.0	037.0	13.0	0	0	0	0	.	011.0	115.5	031.0
071.0	018.0	4.0	0	0	0	0	0	0	051.0	016.5	098.0
070.1	020.8	047.0	0	0	0	0	0	31.5	011.0	090.5	043.5
029.0	022.5	113.3	0	0	0	0	0	0	0	095.0	046.0
078.0	079.5	018.0	.	0	0	0	0	.	8.1	6.0	117.5
3.0	014.0	030.0	.	0	0	0	0	0	012.0	023.5	052.0
122.0	5.5	.	0	0	0	0	0	0	0	124.9	3.2

Hannia precipitation in mm 1958-83

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
.	.	.	.	.	.	.	.	0	07.3	14.0	036.0
060.0	098.0	012.0	0	0	0	0	0	0	28.0	10.0	045.0
027.0	0	029.1	0	0	0	0	0	0	0	07.0	021.0
033.0	325.0	005.0	0	0	0	0	0	02.0	12.0	0	0
057.0	095.0	004.0	0	02.0	0	0	0	33.0	26.0	0	155.0
042.0	011.0	009.0	20.0	12.0	0	0	0	0	46.9	60.4	001.0
076.7	069.5	039.3	05.5	0	5.3	2.2	0	0	0	20.1	053.2
114.4	073.5	026.0	28.5	0	0	0	0	05.0	39.0	04.0	0
149.2	014.5	081.2	0	0	0	0	0	0	0	09.0	128.5
034.0	047.0	081.5	04.0	0	0	0	0	04.0	0	0	022.0
037.0	138.0	0	0	0	0	0	0	0	67.0	79.0	055.0
193.0	024.0	055.0	49.0	05.5	4.2	0	0	0	37.5	17.0	106.0
069.0	070.0	045.0	10.3	04.4	0	0	0	14.0	40.0	84.0	004.0
133.0	136.0	017.0	04.0	03.0	0	0	05.	14.0	09.0	95.0	071.0
036.0	055.5	026.8	55.1	0	0	0	0	03.0	103.0	26.0	097.1
047.0	076.0	063.0	13.0	06.0	0	0	0	0	110.0	140.0	040.0
048.0	029.0	043.0	0	0	0	0	13.	0	07.0	37.0	115.1
138.7	021.0	014.0	52.0	0	0	0	0	0	02.5	27.5	070.0
145.0	045.0	012.0	0	0	0	0	0	0	16.0	05.0	016.0
032.9	018.5	002.0	32.2	0	0	0	0	24.0	18.0	25.0	274.7
231.0	140.8	052.0	0	0	0	0	0	0	123.0	11.5	105.0
068.4	036.3	015.9	05.5	0	0	0	0	01.0	04.1	61.3	049.3
020.4	012.5	008.5	0	0	0	0	0	0	0	0	028.0
233.0	109.0	001.5	0	0	0	0	0	0	18.4	153.9	041.1
016.8	035.8	063.8	04.7	0	0	0	0	27.5	06.0	27.0	061.0
097.0	032.0	028.0	0	0	0	0	0	.	.	.	.

Slonta precipitation in mm 1967-83

	Jan	Feb	Mar	Apr	May	Jun	J	A	S	Oct	Nov	Dec
1967	39.6	35.2	0	0	0	0	0	0	0	26.9	5.4	30.5
1968	119.9	12.0	79.1	0.9	0	0	0	0	0	37.0	70.0	69.0
1969	175.5	23.0	52.0	48.0	0	0	0	0	0	0	18.0	8.0
1970	54.0	26.0	35.6	35.2	0	0	0	0	1	27.0	49.5	8.0
1971	83.5	91.0	6.0	17.4	7.4	0	0	0	0	21.0	75.5	40.0
1972	14.0	63.5	27.0	10.0	9.0	0	0	0	0	63.0	18.0	15.0
1973	48.0	66.4	46.0	14.0	0	0	0	0	0	41.0	25.0	10.5
1974	128.2	16.0	31.0	0	0	0	0	0	0	2.0	9.5	61.5
1975	71.5	24.5	3.5	9.0	0	0	0	0	0	20.0	20.0	46.1
1976	117.7	47.1	46.9	2.6	0	0	0	0	1.4	12.3	34.5	14.8
1977	37.0	9.5	25.8	44.9	0	0	0	0	0	0	17.9	226.5
1978	15.6	104.7	58.1	0	0	0	0	0	0	87.5	7.1	71.0
1979	77.0	68.0	0	0	0	5	0	0	0.3	22.3	71.0	112.1
1980	47.0	100.3	27.7	0	0	0	0	0	0	0	0	9.8
1981	243.7	171.0	0	5	15	0	0	0	0	16.0	87.1	28.5
1982	41.0	91.0	45.0	30.0	0	0	0	0	0	0	35.0	66.0
1983	70.0	32.8	101.0	0	4.3	0	0	0	.	.	.	.

Bayyada precipitation 1958-1990 (mm)

Jan	Feb	Mar	Apr	May	Jun	J	Aug	Sep	Oct	Nov	Dec
.	.	.	.	0	0	0	0	0	0	06.0	23.0
115.0	61.0	08.0	02.0	0	0	0	0	0	36.0	14.0	82.0
49.5	31.0	37.5	10.0	0	0	0	0	0	0	37.0	86.0
85.5	281.5	20.0	04.0	0	0	0	0	0	25.0	.	115.0
79.0	97.0	06.0	01.0	0	0	0	0	12.0	39.0	05.0	172.0
90.0	46.0	22.0	09.0	19.0	0	0	0	0	18.2	28.0	02.5
64.3	39.5	33.0	0	0	0	0	0	0	02.0	57.0	62.0
111.0	66.5	43.5	31.5	0	0	0	0	0	25.5	18.0	85.5
140.0	39.5	58.0	09.0	0	0	0	0	9.0	0	30.0	83.0
25.0	40.5	33.0	13.0	0	0	0	0	0	19.0	17.2	14.0
156.5	26.0	29.0	0	0	0	0	0	21.0	23.0	70.0	58.0
234.4	.	39.0	27.0	0	0	0	0	0	10.5	29.0	116.0
22.0	33.0	15.0	0	0	0	0	0	0	12.0	27.0	.
60.0	72.0	63.0	21.0	0	0	0	0	0	0	0	3.0
56.0	47.0	24.0	100.5	10.0	0	0	9.0	0	48.0	13.0	35.0
64.5	57.0	60.0	12.0	5.0	0	0	0	0	24.0	36.0	33.0
94.0	41.5	33.0	05.0	0	0	0	0	0	19.0	.	.
31.0	.	.	10.0	0	0	0	0	0	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
27.0	09.0	09.0	11.0	0	0	0	0	17.0	0	29.0	154.5
61.0	62.0	89.0	0	0	0	0	11.0	0	105.0	.	51.0
48.0	27.0	0	0	0	0	0	0	0	.	.	18.0
.	109.0	0	0	0	0	0	0	0	11.0	.	68.0
269.0	68.0	0	0	3.0	0	0	0	0	4.0	111.3	26.0
38.0	77.0	.	0	0	0	0	0	0	.	.	.
79.0	.	38.5	02.0	0	0	0	7.0	.	11.0	20.0	.
41.5	39.0	17.0	31.5	0	0	0	0	0	0	104.0	61.0
126.5	66.0	11.5	0	0	0	0	0	0	73.0	27.0	87.0
51.0	19.5	19.0	0	47.5	0	0	0	17.4	74.0	30.0	147.7
09.3	05.5	21.0	10.0	0	0	0	0	0	0	0	14.5
15.0	75.5	29.5	0	0	0	0	0	0	0	.	43.5
.	.	.	0	0	0	0	0	0	17.0	35.8	32.8
67.7	24.3	.	0	0	0	0	0	0	0	51.5	11.0

Daily rainfall

Shahhat, daily precipitation in mm (1981-93)

1981

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	8.4	0	0	0	15.0	0	0	0	0	0	0	0
2	12.3	0	0	0	0.6	0	0	0	0	0	0	0.5
3	2.6	0	0	0	0	0	0	0	0	0	0	0
4	0	16.2	0	0	0	0	0	0	0	0	0	0
5	8.2	0	0	0	0	0	0	0	0	0	0	7.0
6	1.2	29.1	0	1.0	0	0	0	0	0	0	0	8.3
7	40.0	26.0	0	0	0	0	0	0	0	0	0	0
8	7.0	7.0	0	0	0	0	0.2	0	0	0	5.0	0
9	31.5	0	0	0	0	0	0	0	0	0	6.9	0
10	27.2	0	0	0	0	0	0	0	0	0	7.0	0
11	0	0	0	0	0	0	0	0	0	0	20.3	0
12	0	0	0	0	0	0	0	0	0	0	3.6	6
13	0	0	0	0.5	0	0	0	0	0	0	3.0	0
14	0	0.8	0	tr	0	0	0	0	0	0	4.0	0
15	13.5	0	0	0	0	0.8	0	0	tr	0	17.1	1.0
16	18.4	1.0	0	0	0	0	0	0	0	0	1.4	0
17	0	12.0	0	0	0	0	0	0	0	0	5.2	0
18	3.3	18.4	8.7	0	0	0	0	0	0	0	5.6	0
19	15.0	3.2	4.0	0.2	0	0	0	0	0	1.2	0	0
20	5.8	0	0	0.1	0	0	0	0	0	4.3	0	1.8
21	0.6	0	0	0	0	0	0	0	0	0.7	0	0
22	tr	12.8	0	0	0	0	0	0	0	0	0	0
23	28.6	25.7	2.5	0	0	0	0	0	0	0	0	22.8
24	20.0	0	0	0	0	0	0	0	0	0	0	0
25	27.8	0	0	0	0	0	0	0	0	0	5.0	0
26	3.8	0	0	0	0	0	0	0	0	0	1.0	11.5
27	35.6	0	0	0.4	0	0	0	0	0	0	28.6	0
28	9.0	0	0	0	0	0	0	0	0	0.5	13.0	0
29	3.4	0	0	0	0	0	0.1	0	0	0	0	0
30	6.5	0	0	0	0	0	0	0	0	0	19.6	0
31	2.6	0	0	0	0	0	0	0	0	1.0	0	0

1982

1	0	14.0	3.2	0	0	0	0	0	0	0	0	0
2	0	1.6	1.0	0.2	0	0	0	0	0	0	0	0
3	0	1.0	8.8	0.2	0	0	0	0	0	0	0	0
4	0	2.0	0	0	0	0	0	0	0	0	0	12.0
5	0	10.0	0	0	0	0	0	0	0	0	6.0	0
6	0	0	0	0	0	0	0	0	0	0	1.3	1.8
7	0	0	4.9	0	0	0	0	0	0	0	15.0	0
8	7.7	0	7.8	0	0	0	0	0	0	0	0	0
9	0	0.3	1.0	0	0	0	0	0	0	0	0	0
10	0	15.7	0	0	0	0	0	0	0	0	0	0.5
11	0	17.0	0	0	0	0	0	0	0	0	0	0
12	0	13.2	0	0	0	0	0	0	0	0	0	24.0
13	0	0	0	0	0	0	0	0	0	0	0	1.1
14	2.0	1.2	0	0	0	0	0	0	0	0	0	0
15	0	0	1.0	0	0	0	0	0	0	0	0	0
16	0.9	0	0	0	0	0	0	0	0	0	0	0.5
17	1.0	0	0	0	0	0	0	0	0	0	5.0	0
18	0	0	0	0	0	0	0	0	0	0	7.7	0
19	0	6.1	0	0	0	0	0	0	0	0	26.0	11.3
20	0	0.5	0	0	0	0	0	0	0	0	1.0	20.4
21	0	4.5	0	0	0	0	0	0	0	0	0	0
22	0	1.5	1.6	1.0	0	0	0	0	0	0	0	0
23	0	0.5	12.7	0	0	0	0	0	0	0	0	0
24	0	0	0.3	0	0	0	0	0	0	0	0	0
25	0.6	3.0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	1.0	0	11.2
27	0	9.0	0	2.6	0	0	0	0	0	0	0	0
28	0	10.5	0	13.0	0	0	0	0	0	1.0	0	0.5
29	6.0	0	0	0	0	0	0	0	0	0	0	11.0
30	22.0	0	0	0	0	0	0	0	0	0	0	27.6
31	1.0	0	0	0	0	0	0	0	0	0	0	12.0

1983

1	1.0	8.0	1.0	0	0	0	0	0	0	0	0	0
2	15.5	0	9.0	0	0	0	0	0	0	0	0	1.0
3	11.0	8.7	30.0	0	0	0	0	0	0	0	0	0
4	3.2	1.0	20.0	0	0	0	0	0	0	0	6.4	0
5	29.5	14.3	0	0.5	0	0	0	0	9.0	0	0	0
6	2.5	0	0	0	0	0	0	0	0	0	0	5.4
7	13.9	0	0	0	0	0	0	0	0	0	1.4	0.2
8	1.4	0	0	0	0	0	0	0	0	5.0	0	12.0
9	0.5	0	0	0	3.0	0	0	0	0	1.0	18.0	10.8
10	1.5	0	0	0	0	0	0	0	0	0	13.3	4.8
11	1.0	0	0	0	0	0	0	0	0	0	6.2	0
12	4.1	5.1	0	0	3.9	0	0	0	0	0	4.2	0
13	0	0	7.3	0	0	0	0	0	0	0	10.6	0
14	0	0	0	0	0	0	0	11.0	0	0	0	0
15	1.7	0	0	17.0	0	0	0	2.5	0	0	0	5.0
16	25.0	0	0	6.0	0	0	0	0	0	0	0	0
17	3.0	4.0	0	1.6	0	0	0	0	0	0	0	0
18	0	2.0	0	0	0	0	0	0	0	0	3.0	0
19	0	4.0	20.0	0	0	0	0	0	0	0.5	5.0	0
20	2.2	11.9	17.0	0	0	0	0	0	1.0	0	0	0
21	18.0	0.3	0	0	0	0	0	0	0	0	0	0
22	19.5	0	0	0	0	0	0	0	4.0	3.2	0	0.6
23	0	0	0	0	0	0	0	0	0	0	0	1.5
24	0	2.0	0	0	0	0	0	0	0	0	0	0
25	0	5.4	0	0.4	0	0	0	0	3.0	0	0	0
26	0	3.1	0	0	0	0	0	0	0	1.5	25.5	0
27	0	0	0	0	0	0	0	0	0	21.0	26.0	0
28	0	0	0	0	0	0	0	0	0	13.7	3.6	0
29	1.0	0	0	0	0	0	0	0	0	0.9	5.6	0
30	0	0	0	0	0	0	0	0	0	0	10.6	0
31	12.5	0	0	0	0	0	0	0	0	0	0	20.6

1984

1	5.2	0	0	0	0	0	0	0	0	0	27.8	0
2	1.6	0	0.5	0	0	0	0	0	0.4	0	71.2	0
3	0	0	0.5	0	0	0	0	0	0	0	7.8	0
4	0	0	0	0	0	0	0	0	0	0	2.6	0
5	0	1.0	2.3	6.0	0	0	0	0	0	0	0	0
6	0.4	16.7	5.7	1.4	0	0	0	0	0	0	0	9.3
7	4.8	2.9	0	10.5	0	0	0	0	0	0	0	0
8	2.0	0.5	11.1	8.0	0	0	0	0	0	0	0	0
9	0	1.0	21.6	6.4	0	0	0	0	0	0	0	0.2
10	0	3.0	3.4	0	0	0	0	0	0	0	0	2.2
11	0	2.7	0	0	0	0	0	0	0	0	0	4.0
12	29.4	6.6	0	0	0	0	0	0	0	0	0	0
13	10.2	1.0	0	0	0	0	0	0	0	0	6.2	0
14	27.4	0.9	0	0	0	0	0	0	0	0	0.6	0
15	0	0	2.0	0	0	0	0	0	0	0	0.5	0
16	0	0	2.0	0	0	0	0	0	0	0.5	5.1	0
17	0	0.7	1.3	0	0	0	0	0	0	2.9	0	0
18	0	0	0	1.7	0	0	0	0	0	0	0	0
19	0.4	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	8.8	0	0	0	0	0	0	1.1	0
21	0	0	0	0	0	0	0	0	0	0	25.0	1.0
22	0	0	0	0.3	0	0	0	0	0	0	15.0	11.2
23	0	0	0	0	0	0	0	0	0	0	0.6	4.0
24	0	0	3.8	0	0	0	0	0	0	0	0	1.5
25	10.8	0	1.4	0	0	0	0	0	0	0	0	7.0
26	1.0	0	0	0	0	0	0	0	0	7.3	0	1.0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	4.8	0	0
31	0	0	0	0	0	0	0	0	0	14.0	0	0

1985

1	3.6	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0.3	0
7	0	0	0	0	0	0	0	0	0	1.0	17.5	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	3.4	0	0	0	13.0	0	0	0	0	0	0	0
10	0	0	0	0	0.5	0	0	0	0	0	0	0
11	1.0	0	0	0	0	0	0	0	0	0	0	0
12	1.0	0	0	0	0	0	0	0	0	0.6	0	0
13	16.8	0	0	0	0	0	0	0	0	0.2	0	0
14	0	0	0	0	0	0	0	0	0	17.0	0	0
15	0	0	0	0	0	0	0	0	0	6.0	0	0
16	9.2	0	0	0	0	0	0	0	0	22.4	0	54.0
17	38.8	0	0	0	0	0	0	0	0	37.4	0	1.0
18	2.6	0	0	0	0	0	0	0	0	7.1	0	0
19	11.0	0	0	4.0	0	0	0	0	0	0	0	0.5
20	0.5	0	0	15.0	0	0	0	0	0	0	0	6.0
21	0	0	0	2.0	0	0	0	0	0	0	0	21.4
22	0	0	0	0	0	0	0	0	0	0	0	4.3
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0.1	0	17.2	0
25	0	0	0	0	0	0	0	0	0	0	1.0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	16.4	0	0	0	0	0	0	0	0	0	0	0
29	12.0	0	0	0	0	0	0	0	0	0	2.0	0
30	17.0	0	0	0	0	0	0	0	0	0	0	0
31	14.8	0	0	0	0	0	0	0.5	0	0	0	0

1986

1	0	0.2	0	0	29.0	0	0	0	0	0	7.0	0
2	9.1	0	0	0	0	0	0	0	0.6	0	4.0	7.8
3	0	0.4	0	0	0	0	0	0	0.5	0	0	0
4	0	2.0	0	0	0	0	0	0	0	0	0.5	0
5	0	6.0	0	0	0.5	0	0	0	0	0	0	0
6	5.0	0	0	0	0	0	0	0	0	0	7.7	7.7
7	7.0	0	0	0	0	0	0	0	0.3	0	8.2	1.0
8	17.6	7.4	0	0	0.3	0	0	0	0	0	0	6.6
9	0	0	0	0	0	0	0	0	0	0	0	0
10	5.4	0	0	0	0	0	0	0	0	0	0	0
11	13.2	0	0	0	2.0	0	0	0	4.6	0	0	0
12	1.0	0	0.5	0	0	0	0	0	0	0	0	3.3
13	4.2	4.0	2.0	0	0	0	0	0	0	0	0	0
14	9.9	1.9	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	11.5	1.1	0	0	0	0	0	0	0	0	0
17	4.2	0.2	5.3	0	0	0	0	0	0	0	0	7.4
18	0	0	0	0	0	0	0	0	0	0	0	18.2
19	0	0	0	0	0	0	0	0	0	0	0	2.5
20	0	0	10.0	0	0	0	0	0	0	0	0	2.3
21	0.4	0	14.3	0	0	0	0	0	3.6	2.0	0	8.1
22	1.8	0	12.0	0	0	0	0	0	6.4	0	0	0
23	1.0	0	1.7	0	0	0	0	0	20.0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	20.2	0	0	0	0	0	0	0	0	0	0	18.0
26	1.0	0	0	0	0	0	0	0	0	0	0	16.7
27	5.0	0	8.0	0	0	0	0	0	0	6.0	29.7	2.0
28	3.4	0	7.4	0	0	0	0	0	0	0	3.0	12.0
29	0	0	0.2	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	12.0	0	12.4
31	0	0	0	0	0	0	0	0	0	0	0	1.0

1987

1	0	0	26.8	1.3	0	0	0	0	0	0	6.9	0
2	0	12.1	10.2	1.9	0	0	0	0	0	0	0	tr
3	0	0	2.8	0	0	0	0	0	0	0	0	0.1
4	36.7	0	36.0	0	0	0	0	0	0	0	0	0
5	6.2	0	5.0	0	0	0	0	0	0	0	14.7	0.5
6	2.2	0	18.2	0	0	0	0	0	0	0	0	0
7	0	5.2	6.8	0	0	0	0	0	0	0	2.0	0
8	4.6	1.8	10.5	0	0	0	0	0	0	0	0	0
9	4.6	0	3.9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	5.6
11	0	0	2.0	0	0	0	0	0	0	0	0	12.0
12	0	0	0.7	0	0	0	0	0	0	0	27.8	0
13	0	1.8	0	0	0	0	0	0	0	0	3.5	0
14	0	0	0.2	19.6	0	0	0	0	0	0	0	0
15	0	2.2	5.6	9.0	0	0	0	0	0	0	0	0
16	0	0	0	6.7	0	0	0	0	0	0	0	9.3
17	0	0	0	3.0	0	0	0	0	0	0	9.9	27.9
18	0	0	0	0	0	0	0	0	0	0	2.6	0.9
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0.9	12.0
21	0	0	0	0	0	0	0	0	0	0	2.6	19.4
22	6.1	0	0	0	0	0	0	0	0	0	2.9	3.0
23	4.9	21.0	3.0	0	0	0	0	0	0	0	0	0
24	9.2	5.2	4.7	0	0	0	0	0	0	0	0	19.9
25	7.4	2.3	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	6.2	0	2.0	0	0	0	0	0	0	0	0
29	0	0	0	16.4	0	0	0	0	0	0	0.2	0
30	0	0	0	2.0	0	0	0	0	0	0	0	0
31	0	0	27.0	0	0	0	0	0	0	2.6	0	7.0

1988

1	2.0	3.2	0	0	2.3	0	0	0	0	3.2	20.6	0
2	0	0	0.3	0	0	0	0	0	0	0	0	0
3	4.7	0	4.6	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	8.7
5	0	0	0	0	0	0	0	0	0	0	1.0	10.6
6	0	0	5.9	0	0	0	0	0	0	0	0	0
7	0	0	20.0	0	0	0	0	0	0	0	0	0
8	0	0	21.0	0	0	0	0	0	0	0	0	0
9	0	0	5.0	0	0	0	0	0	0	0	0	9.2
10	7.0	0	1.0	0	0	0	0	0	0	0	0	4.6
11	12.0	11.6	2.6	0	0	0	0	0	0	0	0	0
12	0	0	11.0	0	0	0	0	0	0	0	0	0
13	0	14.5	0	0	0	0	0	0	0	0	0	1.6
14	0	29.0	0	0	0	0	0	0	0	0	0	6.8
15	3.0	15.7	0	0	0	0	0	0	0	0	0	0.4
16	2.4	15.2	0	0	0	0	0	0	0	0	1.0	6.9
17	0	8.0	0	2.2	0	0	0	0	0	10.8	18.0	37.5
18	0	0	0.6	0	0	0	0	0	0	0	0	17.8
19	0	1.0	1.2	0	0	0	0	0	0	0	0	44.0
20	0	3.4	0	0	0	0	0	0	0	0	0	0.5
21	0	0	0	0.2	0	0	0	0	0	0	0	0
22	19.0	3.4	0	0	0	0	0	0	0	0.4	0	0.6
23	21.6	1.1	0	0	0	0	0	0	0	0	0	16.5
24	6.8	3.2	0	0	0	0	0	0	0.4	0	0	7.5
25	0	1.0	0	0	0	0	0	0	0	26.2	0	1.0
26	2.0	0	0	0	0	0	0	0	3.0	18.1	2.9	0
27	0	7.0	0	0	0	0	0	0	0.5	36.6	0	0
28	0	1.1	0	0	0	0	0	0	0	9.0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	67.7
30	0	0	0	0	0	0	0	0	0	0	0	21.1
31	13.0	0	0	0	0	0	0	0	0	0	0	0.7

1989

1	0.5	0.7	0	0	0	0	0	0	0	1.0	0	0
2	3.5	9.0	0	0	0	0	0	0	0	13.0	0	1.4
3	2.5	0	0	0	2.3	0	0	0	0	15.5	0	0.6
4	0	0	0	0	0	0	0	0	0	9.0	0	0.5
5	0	5.6	2.5	0	0.4	0	0	0	0	0	0	0
6	0	3.1	12.2	0	0	0	0	0	0	0.8	0	0
7	0.6	3.6	0	0	0	0	0	0	0	0.6	0.3	0
8	32.9	0.9	0.8	0	0	0	0	0	0	0	9.1	0
9	7.7	0	0	0	0	0	0	0	0	0	0	0
10	0	6.3	0	0	0	0	0	0	0	0	0.3	10.8
11	0	6.2	86.5	0	0	4.0	0	0	0	0	8.0	8.0
12	0.1	3.0	36.2	0	0	0.3	0	0	0	0	5.2	0
13	0	0	8.5	0	0	0	0	0	0	0	22.0	1.8
14	0	4.2	0.2	0	0	0	0	0	0	0	3.0	0
15	0	0	0	0	0	0	0	0	0	0	6.0	0
16	0	0	0	0	0	0	0	0	0.4	0.1	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	16.2	0	0	0	0	0	0	0	0	0	0
19	0.1	4.8	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	1.7	0	0	0	0	0	0	0	0	0
22	0	0	9.4	0	0	0	0	0	0	0	0	0
23	0	0	8.0	0	0	0	0	0	0	0	0	0
24	0	0	19.7	0	0	0	0	0	0	0	0	2.0
25	2.7	0	23.1	0	tr	0	0	0	0	0	0	1.0
26	53.3	0	21.3	0	0	0	0	0	2.0	0	0	4.0
27	5.7	0	0	0	0	0	0	0	0	0.2	0.7	3.0
28	0.8	0	0	0	0	0	0	0	0	0	14.4	0
29	7.5	0	0	0	0	0	0	0	0	0	2.0	1.0
30	1.7	0	0	0	0	0	0	0	0	0	0.4	0
31	0	0	0	0	0	0	0	0	0	0	0	1.0

1990

1	3.8	0	0	0	0	0	0	0	0	0	0	0
2	16.0	4.0	0	0	0	0	0	0	0	0	0	6.0
3	14.0	0.1	0	0	0	0	0	0	0	0	0	14.0
4	5.0	0	1.5	2.0	0	0	0	0	0	0	0	0.6
5	4.0	0	0	0	0	0	0	0	0	0	0	0
6	33.4	2.5	0	0	0	0	0	0	0	0	0	0
7	0.3	24.0	0	0	0	0	0	0	0	0	0	0.3
8	0	2.1	0	0	0.4	0	0	0	0	0	6.7	0
9	0	0	0	0	0	0	0	0	0	0	11.0	0
10	0	10.5	0	0	0	0	0	0	0	0	0	0
11	0	0.1	2.6	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	6.5	0	4.3	0.3
13	0	6.3	0	0	0	0	0	0	0	0	0.5	2.0
14	0.1	1.0	0	0	0	0	0	0	4.0	0	1.0	0
15	6.5	0	0	0	0	0	0	0	0	0	0	0
16	7.4	1.4	7.0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0.3	0	0	0	0	0	0	0	0	0
19	5.3	0	0	2.6	0	0	0	0	1.0	0	29.4	0.2
20	12.0	0	0	0	0	0	0	0	0	0	0.2	0.3
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	22.0	0	0	0	0	0	0	0	0	0	0
23	0	0.5	0	0	0	0	0	0	0	3.5	0	0
24	0.1	0	0	0	0	0	0	14.5	0	0	0	0
25	36.0	0	0	0	0	0	0	0	0	0	0.2	0
26	0.3	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	5.0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	2.0	25.0
30	16.3	0	0	0	0	0	0	0	0	0	0	12.0
31	8.4	0	0.3	0	0	0	0	0	0	0	0	0

1991

1	0	11.3	0	0	0	0	0	0	0	0	52.0	0
2	0	4.6	0	0	0	0	0	0	0	0	3.0	24.0
3	0	4.8	6.1	0	0	0	0	0	0	0	0	0
4	0	0	0.5	0	0	0	0	0	0	1.0	0	0
5	0.3	0	0	0	0	0	0	0	0	0	0	10.0
6	3.5	0	0	2.0	0	0	0	0	0	0	0	25.5
7	6.8	1.6	0	5.5	0	0	0	0	0	0	8.0	40.7
8	0	0	0	0.2	0	0	0	0	0	0	6.0	11.3
9	0.2	0	0	0	0.6	0	0	0	2.5	3.0	4.0	14.5
10	0.5	0	0	0	tr	0	0	0	0.4	0	0	25.9
11	0	0	1.0	0	1.0	0	0	0	0	0	3.2	14.0
12	0	1.3	0.6	0	1.6	0	0	0	0	0	12.5	17.0
13	0	tr	0	0	2.0	0	0	0	0	0	0	0
14	0	0	0	0	4.5	0	0	0	0	0	0	0
15	0	12.0	0	0	0	0	0	0	0	0	0	0
16	2.0	1.0	2.0	0	0	0	0	0	0	0	0	0
17	0	0	6.0	0	0	0	0.6	0	0	0	2.0	0
18	29.8	0	0	0	1.0	0	0	0	0	0	4.5	0
19	1.0	0	0	0	0	0	0	0	0	0	0	33.0
20	13.0	0	0	0	0	0	0	0	0	0	0	5.5
21	1.5	4.1	0	0	0	0	0	0	0	0	0	13.2
22	tr	2.4	0	0	0	0	0	0	0	0	0	32.9
23	0.2	11.0	0	0	0.7	0	0	0	0	0	0	16.0
24	0	23.0	0	0	7.0	0	0	0	0	0.3	0	1.0
25	1.0	17.3	0	0	0	0	0	0	0	13.0	0	16.0
26	0	12.1	0	8.5	0	0	0	0	0	0	0	86.5
27	0	0.1	0	0	0	0	0	0	0	0	5.8	5.1
28	1.2	0	0	0	6.2	0	0	0	0	0	10.5	18.9
29	17.8	0	0	0	0	0	0	0	0	0	1.0	4.8
30	12.2	0	0	8.0	0	0	0	0	0	0	1.0	8.9
31	3.0	0	0	0	0	0	0	0	0	0	0	11.0

1992

1	0.9	6.6	0	0	0	0	0	0	0	0	0	2.5
2	0	20.2	0	0	0	0	0	0	0	0	0	0
3	0	3.0	0	0	0	0	0	0	0	0	0	0
4	0	7.0	0	0	0	0	0	0	0	0	0	0
5	0	54.2	0	0	0	0	0	0	1.5	0	0	0
6	0	0	0	0	10.5	0	0	0	0	0	0	7.5
7	0	0	0	2.5	5.9	0	0	0	0	0	0	5.1
8	0	10.7	tr	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0.2	0
10	0	0.4	0	0	0	0	0	0	0	0	0	0
11	0	0	12.6	0	0	0	0	0	0	0	7.2	3.0
12	0	0	1.0	0	0	0	0	0	0	0	17.8	10.8
13	0	0	0.7	0	0	0	0	0	0	0	9.9	25.4
14	0.4	0	0	0	0	0	0.4	0	0	0	32.0	2.0
15	1.3	15.9	0	0	0	0	tr	0	0	0	0	10.0
16	0	3.0	2.9	0	0	0	0	0	0	0	0	0
17	0	0	4.0	0	0	0	0	0	0	0	0	0
18	1.6	tr	5.4	1.1	0	0	0	0	0	0	0	1.0
19	1.0	0	1.3	0	0	0	0	0	0	0	10.5	8.8
20	2.9	1.0	0	3.2	0	0	0	0	0	0	5.5	10.0
21	0	8.0	0	0	0	0	0	0	0	0	0	0
22	0	19.5	0	0	0	0	0	0	0	0	1.1	0.5
23	0	1.0	0	0	0	0	0	0	0	0	0	16.0
24	0.2	3.6	tr	0	0	0	0	0	0	0	0	2.0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	1.6	0	0	0	0	0	0	0	0	0	0	0.3
28	1.0	0	0	0	0	0	0	0	0	0	0	0
29	14.5	0	3.1	0	0	0	0	0	0	0	0	0
30	3.2	0	0	0	0	0	0	0	0	0	13.2	0
31	13.0	0	0	0	0	0	0	0	0	0	0	0

1993

1	17.1	5.0	0.2	0	0	0	0	0	0	0	0	0
2	18.3	0.5	0	0	0	0	0	0	0	0	0	0
3	0.5	1.0	0	0	0	0	0	0	14.0	0	0	0
4	1.8	0	0.2	0	0	0	0	0	0	0	0	0
5	84.5	0	2.0	0.4	0	0	0	0	0	0	0	3.6
6	48.0	0	18.7	0	0	0	0	0	0	0	0	0.6
7	4.6	0	18.0	0	0	0	0	0	0	0	0	0
8	0	0	9.0	0	9.6	0	0	0	0	0	0	2.5
9	0	0	0	0	0	0	0	0	0	0	0	3.0
10	0	0	0	0	0	0	0	0	0	0	0	1.0
11	0	2.4	0	0	0	0	0	0	0	0	0	0
12	0	1.0	0	0	0	0	0	0	0	0	0	7.0
13	0	4.4	0	0	0	0	0	0	0	0	0	0
14	0	0.6	0	0	0	0	0	0	0	0	4.0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	1.5	4.4	0	0	0	0	0	0	0	7.3	0
17	0	0.1	4.2	0	0	0	0	0	0	0	1.1	0
18	0	4.5	1.0	0	0	0	0	0	0	0	1.0	0
19	0	0.5	0	0	0	0	0	0	0	0	0	0
20	0	0.7	0	0	0	0	0	0	0	0	0	0
21	0	10.4	0	0	0	0	0	0	1.3	0	1.0	0
22	0	3.0	0	0	0	0	0	0	0	0	0	2.7
23	0	1.3	0	0	0	0	0	0	0	0	1.0	1.0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	9.2	0	0	0	0	0	0	0	0	0	0
26	0.2	1.0	0	0	0	0	0	0	0	0	0	0
27	5.9	0	4.7	0	0	0	0	0	0	0	2.0	0
28	0	0	3.5	0	0	0	0	0	0	0	0.8	0
29	0.4	0	0	0	0	0	0	0	0	43.4	8.1	0
30	5.0	0	0	0	0	0	0	0	0	5.5	0	0
31	3.0	0	0	0	0	0	0	0	0	0	0	18.7

Al-Kouf, daily rainfall in mm (1981)

day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	18.3	2.2	0	1.3	0	0	0	0	0	0	0
2	0	2.0	1.0	0	1.3	0	0	0	0	0	0	0
3	0.1	0	15.8	6.8	0	0	0	0	0	0	0	0
4	0	0.2	1.9	0	0	0	0	0	0	0	0	1.5
5	0	9.1	0.2	0	0	0	0	0	0	0	3.0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0.6	4.2	0	0	0	0	0	0	0	0.7	0
8	4.1	3.3	8.7	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0
10	0	22.3	0	0	0	0	0	0	0	0	0	0
11	0	17.8	0	0	0	0	0	0	0	0	0	0.6
12	0	8.8	0.4	0	0	0	0	0	0	0	0	18.0
13	0	0	0	0	0	0	0	0	0	5.4	0	0
14	0	1.7	0	0	0	0	0	0	0	0	0	0
15	0	0.2	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	6.5	0	7.1	0.6
18	0	0	0	0	0	0	0	0	0	0	6.8	0
19	0	5.2	0	0.4	0	0	0	0	0	0	16.0	11.1
20	0	0	0	0	0	0	0	0	0	0	0.8	17.0
21	0	0.4	0	0.2	0	0	0	0	0	0	0	0
22	0	0.3	0.8	0.4	0	0	0	0	0	0	0	0
23	0	0	7.8	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	2.2	0	0	0	0	0	0	0	0	0	0
26	0.1	1.6	0	0	0	0	0	0	0	0.6	0	6.8
27	0	6.2	0	1.2	0	0	0	0	0	0	0	0
28	0	5.3	0	12.6	0.1	0	0	0	0	1.4	0	1.5
29	9.4	.	0	0	0	0	0	0	0	0	0	18.0
30	21.4	.	0	0	0	0	0	0	0	0	0	16.2
31	0.1	.	0	.	0	.	0	0	.	0	.	3.0

Al-Kouf, daily rainfall in mm (1982)

day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	18.3	2.2	0	1.3	0	0	0	0	0	0	0
2	0	2.0	1.0	0	1.3	0	0	0	0	0	0	0
3	0.1	0	15.8	6.8	0	0	0	0	0	0	0	0
4	0	0.2	1.9	0	0	0	0	0	0	0	0	0
5	0	9.1	0.2	0	0	0	0	0	0	0	0	1.5
6	0	0	0	0	0	0	0	0	0	0	3.0	0
7	0	0.6	4.2	0	0	0	0	0	0	0	0	0
8	4.1	3.3	8.7	0	0	0	0	0	0	0	0.7	0
90	0	0	0	0	0	0	0	0	0	0	0	0
10	0	22.3	0	0	0	0	0	0	0	0	0	0
11	0	17.8	0	0	0	0	0	0	0	0	0	0
12	0	8.8	0.4	0	0	0	0	0	0	0	0	0.6
13	0	0	0	0	0	0	0	0	0	0	0	18.0
14	0	1.7	0	0	0	0	0	0	0	5.4	0	0
15	0	0.2	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	6.5	0	7.1	0.6
19	0	5.2	0	0.4	0	0	0	0	0	0	6.8	0
20	0	0	0	0	0	0	0	0	0	0	16.0	11.1
21	0	0.4	0	0.2	0	0	0	0	0	0	0.8	17.0
22	0	0.3	0.8	0.4	0	0	0	0	0	0	0	0
23	0	0	7.8	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	2.2	0	0	0	0	0	0	0	0	0	0
26	0.1	1.6	0	0	0	0	0	0	0	0.6	0	6.8
27	0	6.2	0	1.2	0	0	0	0	0	0	0	0
28	0	5.3	0	12.6	0.1	0	0	0	0	1.4	0	1.5
29	9.4	.	0	0	0	0	0	0	0	0	0	18.0
30	21.4	.	0	0	0	0	0	0	0	0	0	16.2
31	0.1	.	0	.	0	.	0	0	.	0	.	3.0

Hannia daily rainfall in mm (1981)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	19.0	0	0	0	0	0	0	0	0	0	0	0
4	0	12.0	0	0	0	0	0	0	0	0	0	0
5	0	5.0	0	0	0	0	0	0	0	0	0	22.4
6	3.5	0	0	0	0	0	0	0	0	0	0	1.5
7	0	35.0	0	0	0	0	0	0	0	0	0	0
8	3.5	14.0	0	0	0	0	0	0	0	0	1.1	0
90	0	0	0	0	0	0	0	0	0	0	2.4	0
10	40.0	0	0	0	0	0	0	0	0	0	5.0	0
11	17.0	0	0	0	0	0	0	0	0	0	18.5	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	27.2	0
14	0	0	0	0	0	0	0	0	0	0	4.5	0
15	22.0	0	0	0	0	0	0	0	0	0	15.0	0
16	30.0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	5.1	0
18	12.0	11.0	0	0	0	0	0	0	0	0	0.5	0
19	0	2.0	0	0	0	0	0	0	0	0	0	0
20	0	0	1.5	0	0	0	0	0	0	8.0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	11.0	0	0	0	0	0	0	0	0	0	0	0.5
23	0	18.0	0	0	0	0	0	0	0	0	0	2.7
24	17.0	12.0	0	0	0	0	0	0	0	0	0	0
25	7.0	0	0	0	0	0	0	0	0	0	21.4	0
26	5.0	0	0	0	0	0	0	0	0	0	0	14.0
27	2.0	0	0	0	0	0	0	0	0	0	28.0	0
28	12.0	0	0	0	0	0	0	0	0	0	1.2	0
29	9.0	.	0	0	0	0	0	0	0	0	0	0
30	13.0	.	0	0	0	0	0	0	0	0	24.0	0
31	10.0	.	0	.	0	.	0	0	.	10.4	.	0

Hannia, daily rainfall in mm (1982)

day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	4.0	1.3	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	31.0	0	0	0	0	0	0	0	0	0
4	0	0	2.0	0	0	0	0	0	0	0	0	0
5	0	4.8	0	0	0	0	0	0	0	0	5.0	1.0
6	0	0	0	0	0	0	0	0	0	0	1.0	0
7	0	0	11.0	0	0	0	0	0	0	0	2.0	0
8	0.5	0	10.5	0	0	0	0	0	0.5	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	9.0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	4.0	0	0	0	0	0	0	0	0	0	5.0
13	0	0	0	0	0	0	0	0	0	4.0	0	14.0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	22.0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	8.0	1.0
18	0	0	0	0	0	0	0	0	0	0	9.0	0
19	0	0	0	0	0	0	0	0	5.0	0	0	10.0
20	0	1.4	0	0	0	0	0	0	0	0	2.0	5.0
21	0	1.5	0	0	0	0	0	0	0	0	0	0
22	0	0	3.0	0	0	0	0	0	0	0	0	0
23	0	0	5.0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	2.0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	15.0
27	2.0	8.7	0	1.7	0	0	0	0	0	0	0	0
28	0	2.4	0	3.0	0	0	0	0	0	0	0	0
29	4.5	.	0	0	0	0	0	0	0	0	0	0
30	9.8	.	0	0	0	0	0	0	0	0	0	5.0
31	0	.	0	.	0	.	0	0	.	0	.	5.0

Slonta, daily rainfall in mm (1981)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	15.0	0	0	0	0	0	0	0
2	8.0	0	0	0	0	0	0	0	0	0	0	0
3	9.7	0	0	0	0	0	0	0	0	0	0	0
4	0	30.0	0	0	0	0	0	0	0	0	0	0
5	10.0	50.0	0	0	0	0	0	0	0	0	0	3.5
6	10.0	20.0	0	5.0	0	0	0	0	0	0	0	0
7	0	22.0	0	0	0	0	0	0	0	0	0	0
8	27.0	20.0	0	0	0	0	0	0	0	0	3.0	0
9	15.0	0	0	0	0	0	0	0	0	0	0	0
10	15.0	0	0	0	0	0	0	0	0	0	2.0	0
11	0	0	0	0	0	0	0	0	0	0	10.0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	5.0	0
14	9.0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	9.0	0
16	16.0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	5.0
18	0	0	0	0	0	0	0	0	0	0	2.0	10.0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	13.0	0	0	0	0	0	0	0	0	8.0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	10.0	0	0	0	0	0	0	0	0	0	0	0
23	18.0	29.0	0	0	0	0	0	0	0	0	0	0
24	23.0	0	0	0	0	0	0	0	0	0	0	0
25	28.0	0	0	0	0	0	0	0	0	0	0	0
26	5.0	0	0	0	0	0	0	0	0	0	2.0	10.0
27	0	0	0	0	0	0	0	0	0	0	25.0	0
28	22.0	0	0	0	0	0	0	0	0	0	19.1	0
29	0	.	0	0	0	0	0	0	0	0	0	0
30	5.0	.	0	0	0	0	0	0	0	0	10.0	0
31	0	.	0	.	0	.	0	0	.	8.0	.	0

Slonta daily rainfall in mm (1982)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	16.0	0	0	0	0	0	0	0	0	0	0
3	0	0	15.0	0	0	0	0	0	0	0	0	0
4	0	0	0	10.0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	15.0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	15.0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	15.0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	36.0	0	0	0	0	0	0	0	0	0	5.0
13	0	0	0	0	0	0	0	0	0	0	0	22.0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	5.0	0
19	0	3.0	0	0	0	0	0	0	0	0	27.8	0
20	0	0	0	0	0	0	0	0	0	0	2.2	4.0
21	0	0	0	8.0	0	0	0	0	0	0	0	13.0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	15.0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	4.0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	2.0	0	12.0	0	0	0	0	0	0	0	0
29	20.0	.	0	0	0	0	0	0	0	0	0	0
30	20.0	.	0	0	0	0	0	0	0	0	0	22.0
31	1.0	.	0	.	0	.	0	0	.	0	.	0

Appendix 3

Amount of soil removed by runoff, measured in mm

pin no.	Nov. 1992 slope no. 1	2	3	4	Dec. 1992 1	2	3	4	Jan. 1993 1	2	3	4
1	1.3	0.3	1.0	0.6	0.3	0.2	0.4	0.2	0.6	0.3	0.5	0.6
2	0.5	0.4	0.6	0.5	0.5	0.1	0.6	0.4	0.8	0.1	0.1	0.7
3	0.8	0.3	0.8	0.8	0.6	0.3	0.6	0.5	0.6	0.3	0.6	0.5
4	0.4	0.5	1.3	0.3	0.6	0.1	0.7	0.6	0.5	0.2	0.2	0.2
5	0.9	0.4	0.8	0.4	0.5	0.2	0.3	0.3	0.2	0.0	0.4	0.3
6	0.6	0.3	0.9	0.5	0.4	0.2	0.5	0.4	0.7	0.4	0.4	0.3
7	0.4	0.5	0.8	0.6	0.3	0.3	0.3	0.3	0.4	0.1	0.5	0.4
8	0.5	0.4	0.5	0.4	0.5	0.5	0.5	0.2	0.6	0.5	0.7	0.5
9	0.6	0.5	0.7	0.4	0.5	0.2	0.6	0.2	0.5	0.1	0.6	0.1
10	0.5	0.6	0.6	0.2	0.3	0.3	0.5	0.2	0.6	0.5	0.8	-0.1
11	0.6	0.2	1.5	0.3	0.3	0.3	0.4	0.6	0.9	1.3	0.7	0.3
12	0.7	0.4	0.6	0.7	0.4	0.4	0.5	0.5	0.4	0.5	0.4	0.3
13	0.4	0.5	0.5	0.4	0.2	0.4	0.3	0.5	0.5	0.3	0.3	0.2
14	0.4	0.3	0.9	0.8	0.4	0.2	0.5	0.4	0.7	0.5	0.7	0.7
15	0.3	0.4	0.8	0.7	0.5	0.3	0.7	0.3	0.5	0.4	1.1	0.3
16	0.5	0.3	0.6	0.4	0.4	0.2	0.6	0.6	0.3	0.2	0.4	0.1
17	0.6	0.4	0.4	0.2	0.2	0.3	0.6	0.3	0.6	0.3	0.6	0.5
18	0.5	0.3	0.7	0.1	0.2	0.2	0.7	0.3	0.4	0.6	0.5	0.1
19	0.4	0.2	0.5	0.3	0.3	0.4	0.4	0.4	0.5	0.4	0.5	0.0
20	0.6	0.2	0.9	0.2	0.2	0.2	0.3	0.3	0.4	0.0	0.4	0.2
21	0.3	0.4	0.4	1.0	0.3	0.3	0.4	0.4	0.3	0.0	0.3	0.3
22	0.5	0.2	0.7	0.2	0.3	0.2	0.7	0.8	0.4	0.3	0.5	0.4
23	0.3	0.2	0.6	0.1	0.2	0.1	0.2	0.2	0.3	0.2	0.4	0.3
24	0.4	0.3	0.4	0.3	0.1	0.0	0.3	0.3	0.2	-0.2	0.8	0.6
25	0.3	0.1	0.4	0.4	0.3	0.3	0.4	0.0	0.5	0.1	0.6	0.3
26	0.5	0.2	0.5	0.4	0.2	0.2	0.3	0.4	-0.1	0.1	0.2	0.4
27	0.7	0.2	0.4	0.3	0.3	0.2	0.3	0.3	0.0	0.4	0.4	0.5
28	0.6	0.1	0.6	0.1	0.3	0.2	0.2	0.3	0.0	-0.2	0.5	0.1
29	0.3	0.1	0.3	0.2	0.2	0.1	0.4	0.1	0.6	-0.1	0.6	0.3
30	0.4	0.3	0.5	0.1	0.0	0.1	0.7	0.0	0.4	0.2	0.2	0.0
31	0.3	0.2	0.4	0.3	0.0	0.2	0.2	0.3	0.2	0.2	0.7	0.2
32	0.5	0.1	0.2	0.1	0.1	0.0	0.3	0.5	0.5	-0.1	0.6	0.4
33	0.6	0.0	0.3	0.4	0.1	0.0	0.8	0.1	0.0	-0.1	0.4	0.2
34	0.2	-0.1	0.4	0.3	0.0	-0.1	0.7	0.1	0.1	0.1	0.5	0.2
35	0.3	0.0	0.3	0.1	0.1	-0.2	0.4	0.0	0.0	0.2	0.4	0.3
36	-0.2	-0.2	0.1	0.1	0.1	0.0	0.4	0.0	0.3	0.1	0.7	0.2

	Feb. 1993				Mar. 1993				Apr. 1993			
	1	2	3	4	1	2	3	4	1	2	3	4
1	0.2	0.4	0.1	0.4	0.4	0.3	0.1	0.9	0.4	0.1	0.5	0.6
2	0.3	0.1	0.5	0.3	0.3	0.0	0.5	0.2	0.1	0.1	0.5	0.2
3	0.3	0.2	0.4	0.3	0.4	0.5	0.6	0.7	0.2	0.2	0.4	0.7
4	0.3	0.3	0.4	0.5	0.4	0.4	0.5	0.4	0.2	0.2	0.4	0.5
5	0.2	0.2	0.3	0.5	0.5	0.2	0.4	0.7	0.3	0.1	0.1	0.0
6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
7	0.5	0.4	0.6	0.1	0.6	0.2	0.6	0.3	0.4	0.3	0.6	0.0
8	0.5	-0.8	0.5	0.6	0.6	-0.8	0.7	0.5	0.1	0.0	0.2	0.4
9	0.6	-0.3	0.7	0.3	0.2	-0.3	0.5	0.3	0.5	0.1	0.8	0.0
10	0.5	0.4	0.3	-0.2	0.6	0.4	0.3	0.5	0.4	0.3	0.3	0.1
11	0.6	0.4	0.6	0.5	0.7	0.3	0.6	0.2	0.0	0.0	0.2	0.0
12	0.5	1.0	0.5	0.4	0.3	0.3	0.4	0.1	0.5	0.2	0.5	0.2
13	0.4	0.3	0.1	0.3	0.5	0.4	0.6	0.0	0.4	0.0	0.1	0.0
14	0.4	0.1	0.3	0.4	0.7	0.5	0.5	0.1	0.5	0.3	0.5	0.3
15	0.4	0.4	0.2	0.3	0.2	0.0	0.7	0.3	0.8	0.2	0.3	0.2
16	0.3	0.2	0.5	0.1	0.4	0.0	0.3	0.0	0.3	0.3	0.1	0.1
17	0.5	0.3	0.6	0.4	0.3	0.4	0.1	0.4	0.7	0.0	0.2	0.4
18	-0.1	0.1	0.7	0.5	0.5	0.1	0.5	0.1	0.0	0.1	0.7	0.1
19	0.6	0.0	0.4	-0.1	0.2	0.5	0.2	0.1	0.0	0.2	0.4	0.1
20	0.5	0.4	0.6	0.2	0.0	0.3	0.6	0.0	0.2	0.0	0.6	0.0
21	0.3	0.2	0.1	0.5	0.3	0.0	0.4	0.4	0.3	0.0	0.1	0.0
22	0.5	0.1	0.2	0.3	0.1	0.0	0.4	0.1	0.1	0.1	0.3	0.1
23	0.3	0.1	0.6	0.1	0.0	0.4	0.3	0.3	0.1	0.0	0.0	0.3
24	0.1	0.2	0.9	0.6	0.0	-0.1	0.1	0.0	0.0	0.0	0.2	0.0
25	0.3	-0.1	0.3	0.3	0.5	0.0	0.0	0.1	0.2	-0.2	0.1	0.0
26	0.2	-0.3	0.4	0.5	0.2	0.1	0.1	0.3	0.1	0.0	0.0	0.0
27	0.6	0.0	0.2	0.0	0.3	-0.2	0.3	0.0	0.4	0.2	0.3	0.3
28	0.5	0.3	0.3	0.4	0.0	0.1	0.0	-0.2	0.3	0.1	-0.1	0.2
29	0.1	0.2	0.0	0.3	0.1	0.0	0.2	0.0	0.0	-0.2	0.1	0.1
30	0.4	0.1	-0.1	0.0	0.0	0.1	-0.4	0.0	-0.2	0.1	-0.1	0.1
31	0.3	0.2	0.2	0.1	0.2	0.0	0.2	0.1	0.3	0.0	0.0	0.0
32	0.0	0.0	-0.1	0.2	0.1	0.0	0.1	0.2	0.0	0.0	-0.2	0.0
33	-0.3	0.1	0.0	0.0	-0.3	-0.2	-0.1	-0.3	0.1	0.0	-0.1	-0.1
34	0.0	0.0	0.2	0.0	0.0	-0.4	0.1	0.0	-0.6	0.0	0.1	-0.6
35	0.0	-0.4	0.0	0.1	-0.1	-0.2	-0.2	0.1	0.0	-0.1	0.1	-0.3
36	0.1	-0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.1

Appendix 4

The means and standard errors of soil depth

Area	Slope no.	Slope position	Mean (cm)	Standard error (cm)
Lussaita	1	lower	26.8	1.53
	1	middle	20.0	1.38
	1	upper	19.8	2.75
	2	lower	10.6	0.87
	2	middle	14.0	1.30
	2	upper	19.0	3.59
	3	lower	20.0	1.38
	3	middle	26.6	2.54
	3	upper	24.0	1.67
	4	lower	35.0	1.84
	4	middle	27.0	1.84
	4	upper	31.2	1.83
	5	lower	36.6	1.94
	5	middle	8.8	2.85
	5	upper	23.2	1.43
	6	lower	57.2	0.86
	6	middle	36.8	2.62
	6	upper	43.6	2.58
	7	lower	47.0	1.82
	7	middle	49.0	6.92
	7	upper	22.4	2.79
	8	lower	30.0	4.04
	8	middle	34.8	1.43
	8	upper	19.4	1.36
	9	lower	47.6	9.34
	9	middle	38.2	6.55
	9	upper	8.6	1.21
	10	lower	24.8	2.60
	10	middle	26.0	0.71
	10	upper	20.4	1.17
Bayyada	1	lower	31.0	7.54
	1	middle	54.0	4.69
	1	upper	30.2	2.40
	2	lower	41.6	3.44
	2	middle	22.6	0.68
	2	upper	32.0	1.38
	3	lower	36.6	4.07
	3	middle	44.0	5.68
	3	upper	41.0	3.21
	4	lower	43.0	7.02
	4	middle	30.4	3.14
	4	upper	35.2	2.67
	5	lower	34.4	1.86
	5	middle	40.2	4.21
	5	upper	21.0	1.22
	6	lower	23.6	2.40
	6	middle	12.0	1.58
	6	upper	21.2	0.58
	7	lower	26.0	1.95
	7	middle	27.8	1.93
	7	upper	31.6	5.00
	8	lower	34.4	5.60
	8	middle	43.0	4.40
	8	upper	23.0	2.43
	9	lower	43.4	2.11
	9	middle	47.4	2.86
	9	upper	18.8	0.73
	10	lower	55.4	3.85
	10	middle	42.0	5.74
	10	upper	9.2	1.66

Batta	1	lower	47.0	1.70
	1	middle	31.5	1.89
	1	upper	23.0	1.05
	2	lower	35.6	1.78
	2	middle	31.0	1.30
	2	upper	36.4	3.98
	3	lower	60.0	2.74
	3	middle	48.4	1.33
	3	upper	31.0	6.98
	4	lower	46.4	5.65
	4	middle	41.8	3.68
	4	upper	36.2	2.42
	5	lower	31.6	3.85
	5	middle	29.2	2.92
	5	upper	29.0	4.88
	6	lower	36.2	1.20
	6	middle	21.0	2.05
	6	upper	38.2	2.37
	7	lower	36.0	2.92
	7	middle	33.8	1.91
	7	upper	45.6	6.39
	8	lower	32.0	1.30
	8	middle	27.8	1.98
	8	upper	25.0	1.14
	9	lower	13.0	2.47
	9	middle	27.4	3.63
	9	upper	25.4	1.50
	10	lower	13.0	2.47
	10	middle	13.6	1.96
	10	upper	28.2	2.33
Magra	1	lower	28.6	1.03
	1	middle	25.2	6.34
	1	upper	15.0	0.95
	2	lower	26.8	3.76
	2	middle	21.4	1.94
	2	upper	16.4	6.79
	3	lower	11.8	0.80
	3	middle	19.2	2.71
	3	upper	15.0	1.41
	4	lower	17.6	2.84
	4	middle	15.4	1.03
	4	upper	18.6	2.01
	5	lower	19.4	2.38
	5	middle	22.2	1.71
	5	upper	19.6	2.62
	6	lower	22.2	0.80
	6	middle	24.4	2.80
	6	upper	29.2	3.68
	7	lower	22.6	2.04
	7	middle	20.4	1.69
	7	upper	25.4	0.98
	8	lower	26.4	1.91
	8	middle	21.8	1.28
	8	upper	20.2	1.71
	9	lower	19.6	2.84
	9	middle	23.0	2.66
	9	upper	17.2	0.86
	10	lower	27.4	1.81
	10	middle	35.4	3.44
	10	upper	26.0	3.03

Gobba	1	lower	22.8	3.02
	1	middle	48.6	6.54
	1	upper	92.0	3.74
	2	lower	70.0	5.00
	2	middle	64.6	4.60
	2	upper	31.2	1.07
	3	lower	44.6	0.68
	3	middle	71.0	4.00
	3	upper	20.8	0.66
	4	lower	38.4	4.15
	4	middle	41.8	5.70
	4	upper	27.4	3.53
	5	lower	35.8	2.01
	5	middle	61.2	1.36
	5	upper	55.0	6.36
	6	lower	53.0	2.05
	6	middle	60.6	1.47
	6	upper	60.6	1.50
	7	lower	50.8	5.45
	7	middle	59.2	3.01
	7	upper	25.4	1.44
	8	lower	32.8	6.66
	8	middle	81.0	6.40
	8	upper	16.6	2.16
	9	lower	43.4	5.74
	9	middle	35.8	1.93
	9	upper	55.0	8.06
	10	lower	20.4	3.54
	10	middle	34.0	0.71
	10	upper	24.2	4.61
Shahhat	1	lower	23.2	1.62
	1	middle	17.0	0.84
	1	upper	19.2	0.58
	2	lower	21.2	1.16
	2	middle	16.4	1.12
	2	upper	22.2	3.29
	3	lower	26.2	2.01
	3	middle	21.0	1.58
	3	upper	22.2	1.39
	4	lower	20.6	1.47
	4	middle	18.0	1.47
	4	upper	19.4	1.75
	5	lower	25.8	0.58
	5	middle	21.6	2.01
	5	upper	24.0	1.82
	6	lower	27.6	1.03
	6	middle	16.4	1.17
	6	upper	14.6	2.04
	7	lower	23.4	2.06
	7	middle	18.2	3.34
	7	upper	20.2	2.76
	8	lower	16.8	1.91
	8	middle	28.6	1.96
	8	upper	30.4	3.14
	9	lower	37.8	2.06
	9	middle	41.6	4.88
	9	upper	24.4	2.50
	10	lower	37.8	1.71
	10	middle	24.6	1.86
	10	upper	20.2	

Al-Kouf	1	lower	80.0	2.24
	1	middle	60.0	3.54
	1	upper	50.0	3.54
	2	lower	55.0	4.18
	2	middle	40.0	4.18
	2	upper	40.0	3.54
	3	lower	70.0	6.52
	3	middle	60.0	4.18
	3	upper	55.0	3.54
	4	lower	50.0	3.54
	4	middle	40.0	3.54
	4	upper	35.0	5.48